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Reliability Assessment and Optimization of Water Distribution Systems Explicitly Considering Isolation Valve Locations

Erika Hernandez Hernandez
University of Kentucky, ehernandez@uky.edu

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Erika Hernandez Hernandez, Student

Dr. Lindell Ormsbee, Major Professor

Dr. Timothy Taylor, Director of Graduate Studies

RELIABILITY ASSESSMENT AND OPTIMIZATION OF WATER DISTRIBUTION SYSTEMS EXPLICITLY CONSIDERING ISOLATION VALVE LOCATIONS

DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Engineering
at the University of Kentucky

By
Erika Hernandez Hernandez
Lexington, Kentucky
Director: Dr. Lindell Ormsbee, Professor of Civil Engineering
Lexington, Kentucky
2020

ABSTRACT OF DISSERTATION

RELIABILITY ASSESSMENT AND OPTIMIZATION OF WATER DISTRIBUTION SYSTEMS EXPLICITLY CONSIDERING ISOLATION VALVE LOCATIONS

Water distribution systems have changed the landscape of communities through two services: 1) providing water supply for domestic and industrial use, and 2) providing water required to fight fires. However, a substantial portion of the water infrastructure in the country, as many of other public assets built over 50 years ago, are now reaching the end of their useful life; which combined with rapid growth and changes in demographics have placed water distribution pipe networks at a state that requires revitalization. The aging infrastructure along with the growing threat of natural and man-made disruptions have led water utilities to place a greater emphasis on developing better strategies to minimize the impact on the system users when a failure event occurs (i.e., improve the reliability of the system).

The proposed segment-based analysis considers valve location to estimate the number of pipes taken out of service to seclude the initial pipe break or element failure. The objective of the assessment is to identify critical segments (i.e., smallest set of pipes that can be secluded using the closest isolation valves) and critical valves in a set of real water distribution networks.

The critical elements, the segments or valves that when taken out of service cause the greatest reduction in the supply delivered and the level of service provided, are identified using the performance metrics based on: loss of connectivity, and the failure to meet hydraulic and fire protection requirements. This type of assessment seeks to be a simple method to provide information on critical elements that considers the role of isolation valves, thus offering a more realistic view of the effects of a breakdown. This framework is then used to define valve locations that could offer the improvement in reliability for a given capital investment.

KEYWORDS: Water Distribution System, Reliability Segments, Isolation Valves, Optimization

Erika Hernandez Hernandez

Erika Hernandez Hernandez

08/14/2020

Date

RELIABILITY ASSESSMENT AND OPTIMIZATION OF WATER DISTRIBUTION SYSTEMS EXPLICITLY CONSIDERING ISOLATION VALVE LOCATIONS

By
Erika Hernandez Hernandez

Dr. Lindell Ormsbee
Director of Dissertation

Dr. Tim Taylor
Director of Graduate Studies

08/14/2020
Date

DEDICATION

To my grandparents

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CHAPTER 1. INTRODUCTION

From early times communities have searched and developed solutions to provide access to water. The development of water supply structures and water management practices has always been closely interwoven with the progress of societies and continues to be a pressing challenge for populations around the globe. The American Water Works Association (AWWA 1974) defines water distribution systems as “including all water utility components for the distribution of finished or potable water by the means of gravity storage feed or pumps though distribution pumping networks to customers or other users, including distribution equalizing storage.” Some of the first examples of such systems can be traced as far back as 3000 B.C. For instance, historians have documented the use of extensive systems of hundreds of wells; public fountains; collection, storage, and use of rainwater; closed conduit piping and aqueducts; sewage and drainage infrastructure; and recreational uses of water by the Minoan and Greek civilizations (Biswas 1985; Koutsoyiannis et al. 2008). An early example (3500 B.C.) of the use of water supply pipes, is the palace of Minos at Knossos (Crete). Here, terracotta pipes below the floors provided water to the palace sourced from springs located up to 10 km away (Koutsoyiannis et al. 2008; Mala-Jetmarova et al. 2015). Later, the ancient Greeks constructed extensive tunnel systems and bridges, often referred to as aqueducts, to transport water from more distant sources (Koutsoyiannis et al. 2008). These developments in water infrastructure and management, were later continued by the Romans who incorporated pressurized pipelines and inverted siphons and further increased the scale of the aqueducts (Haut and Viviers 2012). Following the fall of the Roman Empire, the Middle Age period saw an increase of polluted water sources, especially in Europe, accompanied by an observable decline in sanitation and management of water supply (Gray 1940; Mala-Jetmarova et al. 2015). During this period water was often brought into homes by carrying it from a central delivery point. Significant advancements in water management and water quality accelerated during the Renaissance (14th -17th century) with large scale pipeline projects (e.g. London’s watermains, with more than 50 km of pipes constructed of wood, cast-iron and lead), the invention of the microscope, and experimentation in water purification (Angelakis et al. 2012).

In the United States the first municipal piped water supply was established in Boston in 1652, which intended to provide water supply for domestic use and fire protection. This system reflects the major two functions that most water distribution systems continue to have: (1) to provide users with the amount of safe potable water required at an adequate pressure, and (2) to provide adequate fire protection (National Research Council 2006).

The provision of clean water sustains the functions of the communities and human life. Water and wastewater services enable industrial services, commerce, and maintain human health and safety. The operation of water distribution has also contributed to public health by ensuring a supply of treated water, significantly decreasing the loss of life from waterborne diseases and water pollution that was pervasive in the waterways of the United States before the passage of the Clean Water Act (CWA) in 1972, the Safe Drinking Water Act (SDWA) of 1974, and subsequent water quality regulations. (National Research Council 2006; Mala-Jetmarova et al. 2015).

Most people in the United States receive their water from one of the 155,000 active public drinking water systems in the nation. However, a substantial portion of the water infrastructure in the country, as with many of other public assets built over 50 years ago, are now reaching the end of their useful life; which combined with rapid growth and changes in demographics have placed water distribution pipe networks at a state that requires revitalization (AWWA 2012). The urgency of a renewed water infrastructure is further reinforced by the results of the latest ASCE infrastructure report card for the United States (ASCE 2017) where it received a grade of D^+. Moreover, according to the American Water Works Association, upgrading the existing systems in the United States to sustain the water quality standards and meet the current needs of the growing population would require at least one trillion dollars in additional funding (AWWA 2016; ASCE 2017).

The need for reinvestment and renewal is not unique to the water industry. Other sectors like energy and transportation, that also rely on network structures, are facing challenges in improving resiliency and updating antiquated infrastructure. However, the circumstances of the water sector are particularly unique. The regulations in the water sector have been steered mainly by the U.S. Environmental Protection Agency (EPA), whose primary mission is water quality. This means that there is no specific agency that considers the state of infrastructure as it is the case in other sectors (e.g. Energy and Transportation). Considering the increasing number of recent outbreaks affecting public health that could be attributed to the physical infrastructure (e.g. Washington D.C; Flint, Michigan; Newark, New Jersey; Martin County, Kentucky) this structural difference becomes particularly relevant (Renner 2009; Corasaniti 2019; Roy and Edwards 2019; Sellers 2019).

Of the over 150,000 existing public water systems (PWS) in the United States, approximately 6% provide water to more than 92% of the US population. This means that the remaining 8% of the population are served by nearly 120,000 smaller systems, typically serving 3,300 customers or less. The majority of these systems are operated by small municipalities. Unfortunately, many have not been able to maintain their local infrastructure because of constraints imposed by local politics and the expectations of many customers for low-cost water. In addition to such financial challenges, many such systems have found it increasingly difficult to recruit and maintain qualified staff to operate such systems. In the state of Kentucky, many coal-producing counties have relied in the past on coal-severance taxes to fund the water and wastewater infrastructure. With the downturn in the coal industry and the loss of such funds, many communities in eastern Kentucky are falling further behind in the maintenance of their systems, leading to the situation where many systems are now experiencing greater than 50% water loss.

Such problems are further exacerbated by the fact that most of these problems are hidden or out-of-sight because most of the infrastructure is buried below the surface. Even so, it could be said that water distribution systems are fairly reliable when compared to other infrastructure networks, given that the useful life of the distribution network components can very well span from 40 to a 100 years (Mays 2000). Nonetheless, if the vast areas typically served by such systems and the large number of elements involved (e.g. reservoirs and storage tanks, pipes, fittings and accessories, meters, valves, and hydrants) are considered, WDS are still particularly susceptible to multiple malfunctions during their lifetime even with long-lived components. Additionally, a considerable number of these assets are steadily approaching or are well beyond their expected lifespan, contributing to the over 240,000 water main breaks per year in the United States.

The continuing aging infrastructure along with the growing threat of natural and man-made disruptions, have led water utilities to place a greater emphasis on developing better strategies to minimize the impact on the system when a failure event occurs (i.e., improve the reliability of the system). The risk of failure or component malfunction cannot be eliminated completely, but it can be reduced and planned for. Utilities in charge of operating and maintaining the distribution systems must address this concern with limited resources, while maintaining acceptable levels of service, managing risk, and considering the possible socio-economic impact on the community. Also, unlike other sectors utilities are not as well supported by the public. Water systems typically operate as independent units (i.e. they are not part of interconnected national networks like the transportation or energy sector) and are thus subject to local problems and restrictions. Each year that passes results in a natural increase in the deterioration of the water infrastructure, and an associated decline in the reliability of the system.

The main goal of this dissertation research is to focus on a particular component of the water distribution system infrastructure (i.e. isolation valves) as an effective tool or means for improving the reliability and associated resilience of such systems. This goal encompasses several research tasks.

First, computational models of actual water distribution systems will be assembled that include the impact of actual isolation valve locations. These assembled models will then be added to a national research database (i.e. the Kentucky Water Distribution Research Database) that has been created by the University of Kentucky Water Resources Research Institute through a partnership with the American Society of Civil Engineers.

Second, a procedure to identify the subsections of the network that can be isolated by the existing valve layout (i.e. segments) is defined. Third, a segment-based assessment protocol is developed and applied to the assembled systems which then ranks and prioritizes each segment for use in identifying segments for subsequent strengthening so as to minimize the impact (i.e. loss of water supply) in response to critical failure events (i.e. the loss of pipe or critical components in response to pipe breaks or component failures). Finally, a heuristic procedure is developed which prioritizes and optimizes system improvements (e.g. the placement of additional isolation valves or pipe segments) to increase the reliability of the system at a minimum cost. Table 1 summarizes the main research questions and novel methods used to address these research objectives.

Table 1-1 Dissertation Overview

	Title	***Innovative Method/Application***	***Research Question***
1	Introduction		
2	Background		How have other researchers considered the question of reliability? How have graph-based metrics been used? How have hydraulic simulations been used to address the question of system reliability?
3	Segment Identification Protocol for Water Distribution Systems	Segment Identification Tool Development Using EPANET and the MATLAB EPANET Programmers Toolkit. Identification Method conserves the location of the valves, does not require the use of pseudo-elements, and uses minimal user input after a model file is created.	Is there a straightforward and scalable method for segment identification using widely available tools?
4	Segment-Based Assessment of The Consequences of Component Failure on Water Distribution Systems	Definition of WDS Performance criteria that is segment-based and considers: topological principles hydraulic behavior, and fire protection requirements.	Is there a simple metric that can be used as a surrogate for reliability in WDS? Would the use of different metrics consistently indicate the same element as critical? Do different metrics signal different critical components? (i.e. critical segments) Is the use of a pressure dependent demand model necessary or redundant?
5	Valve Placement Optimization	Investigate the use of graph theory concepts to develop an optimal valve placement procedure. Test and compare a performance-based optimization objective (i.e. undeliverable supply) against a network configuration target value (i.e. number of valves per segment).	Could a simple heuristic procedure be developed that could provide guidance on where to place new isolation valves to increase system reliability? Could a change in the topology of the network facilitate the analysis of critical elements? Could a graph transformation approach inform the viable locations for valve layout improvements?
6	Conclusions and Future Research		

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CHAPTER 2. BACKGROUND

Although safe drinking water and sanitation services are a core element of a healthy population and a requirement for societal growth, over 2 billion people continue to lack access to safely managed drinking water (UNICEF and WHO 2019). In the United States, over 286 million people have access to water through a community water system. While the US drinking water supply is considered one of the safest in the world (CDC 2009), it is not free of challenges. For instance, an analysis of the Environmental Protection Agency's records on water quality violation across the country revealed that over a 34-year period, between 1982 and 2015, 9 to 45 million people in any given year received water from a source in violations of the Safe Drinking Water Act (Allaire et al. 2018; Langin 2018). While some of these violations may be linked to regulatory changes (i.e. lowering of contaminant level limits, and introduction of new health standards), a number of populations across the country, particularly in rural counties and small systems, observed persistent water quality violations (Allaire et al. 2018). Small municipalities are pervasively unable to finance or undertake the rehabilitation and expansion needed to maintain the existing distribution system and adapt to the changing conditions (e.g. increase frequency of severe weather events, changing quality standards, growing or dwindling populations, decrease in affordability of water). Thus, the effect of the aging distribution systems on the water quality and the high losses experienced due to leakage are mostly left unaddressed until a catastrophic failure is experienced (Mays 2000; ASCE 2017).

The deteriorating systems face a complex decision-making problem with limited financial and technical resources. The long-term underfunding of water distribution infrastructure has not allowed many utilities to implement the maintenance and expansion projects that existing systems urgently require. All water distribution systems share the common objective of supplying its users with the amount of water required, at an adequate pressure and quality (Mays 2000). Yet, with each year that passes the ability to act on this objective during a given period of time is reduced while the reliability of the system is increasingly diminished. The reliability assessment and isolation valve placement methodology proposed in this research seeks to provide tools to assist in the decision-making process with a goal of increasing overall system reliability and resilience.

The design and analysis of water distribution systems is already a complex problem regardless of funding constraints. It requires defining the layout and the optimum sizing for a wide variety of elements, where due to the interconnected nature of the system the change of one element will affect the whole (e.g., changing a pipe diameter will affect the pressure distribution across the system). Typically, water distribution networks can be divided into major four components: (1) water sources and intake work, (2) treatment works and storage, (3) transmission mains, and (4) the distribution network (Swamee and Sharma 2008). Due the complexity of the system, the current work will focus on the distribution network and its associated elements: tanks, pumps, pipes, and valves. These components must be able to operate under a variety of hydraulic loading conditions (i.e. peak daily demands, varying daily patterns, pipe breaks, and firefighting requirements). The problem the engineer must solve for an existing or a new system consists not only on ensuring the system can operate under a variety of patterns, but to do so reliably and economically. This problem is approached by simulating the hydraulic conditions using a computer program that solves a set of linear and nonlinear hydraulic equations for an associated set of initial and boundary conditions. A set of possible designs are tested under multiple loading patterns (e.g. varied customer demands, emergency conditions) and the distribution of pressures and observed flows are predicted and recorded. Generally, if the resulting pressures are not satisfactory, the designs are revised, and a new hydraulic simulation is performed. Using this iterative process, the components of the network are placed in candidate locations and sized. In the case of the pipelines, this mainly means a selection of possible pipe materials and diameters from a subset of commercially available sizes and pressure limitations. The placement of pumps in the system is used to increase the head (pressure) of the system, while tanks are incorporated to serve as emergency supply storage (for fires) or provide the required demand during peak conditions. In the design and expansion process, valves have a variety of functions such as restricting the direction of flow (i.e. check valves), reducing the head (i.e. pressure reducing valves, pressure regulating valves), limiting discharge (i.e. flow control valve), and blocking flow (i.e. isolation valves). The iterating process of locating and sizing the needed components and then performing hydraulic simulations to assess their performance, continues until a solution is found which satisfied the design objectives for the system, ideally at a minimum cost (Mays 1989).

The use of hydraulic network software (or solvers) has allowed engineers to test an increasing number of component variations and possible loading conditions. However, it is important to note that although the availability of such software has allowed engineers to perform increasingly more complex simulations, a consideration of the role of isolation valves on overall operations, has been more limited (Ozger and Mays 2005). The proposed framework will explicitly examine the role, impact, and location of isolation valves.

2.1 HYDRAULIC NETWORK SYSTEM PROPERTIES

An exploration of the topic of network reliability, by necessity, requires an examination of several other related system properties. These include robustness, resilience, and redundancy. As with reliability, there are varying definitions of these terms, but in the context of water distribution systems and this document the following definitions will be used (Awumah et al. 1991; Cullinane et al. 1992; Xu and Goulter 1999; Zhuang et al. 2013):

Redundancy – a discrete measure of the number of alternative paths (e.g. pipes) or components (e.g. pumps) that exist in a water distribution system sufficient to maintain a specific level of performance.

Resilience – a continuous measure of how much time it takes to restore a level of performance once it has been violated.

Robustness – a measure of how much or many component failures a system can experience before it violates a specific level of performance.

Reliability – the ability of a system to maintain a specific level of performance over a specified period of time.

The interest in reliability of network infrastructure and other system properties often requires a description of the structure itself or the performance of the system. Several of the performance indicators traditionally included for network analysis in water distribution systems have been adapted from graph theory, electrical engineering, and other fields. In some cases, these adapted performance metrics have been redefined to consider cost, water quality, and water pressure. However, as many of these traditional metrics do not naturally yield to such correlations, many of the metrics have been used as implicit or indirect measures of system performance. A summary of some of the more commonly used metrics to estimate these system properties is included in Tables 2-1 through 2-4.

Conventionally the methods used to estimate reliability and other system properties can be identified as: analytical, simulation-based, and heuristic (Mays 1989; Gheisi et al. 2016). The analytical approaches solve for the performance metric under a stringent set of conditions directly using the demands of the network and its layout. Metrics based on graph theory, topology, and probability theory are typically identified as analytical. In using a simulation-based approach, different loading or time scenarios are used to observe the behavior of the network, and the results are then used to evaluate quantitative metrics of system performance. This approach will usually consider performance metrics using hydraulic solvers, Monte Carlo simulations, and similar methods. Finally, heuristic or surrogate-based methods borrow principles from graph theory and hydraulics. The heuristic approaches focus on reflecting changes in reliability but do not measure it precisely (Mays 2000). In previous reviews, the heuristic metrics have been divided in three types: entropy-based, energy/power- based and hybrid surrogate measures (Gheisi et al. 2016). In the case of the proposed approach, the performance metrics used to analyze the behavior of the network are based on emergency conditions and are derived using a combination of analytical metrics and simulation-based assessments.

Although reliability has been constant subject of interest, some practical have aspects only been explored recently. For instance, the placement of additional storage tanks for emergencies, availability of generators, presence of alternative pathways, and valving (Gheisi et al. 2016; Liu et al. 2017; Kim et al. 2019; Giustolisi 2020; Sirsant and Reddy 2020). These are practical measures that designers and operators could take to improve reliability — particularly where valve placement is concerned. The importance of an adequate valve layout can be simply stated when a pipe break occurs, since it is not the link itself but the location of the isolation valves that will determine the extent of the outage. Currently, most assessment assume all links will be able to be isolated (i.e. all pipes will have isolation valves at both ends)(Cullinane et al. 1992; Jowitt and Xu 1993; Gupta and Bhave 1994; Ostfeld et al. 2002; Sweetapple et al. 2018; Paez and Filion 2020) or recognize that the valve placement used is artificially generated (Liu et al. 2017). The assessment and valve placement method presented in this document recognizes the location of the isolation valves in the system and their effect on the reliability.

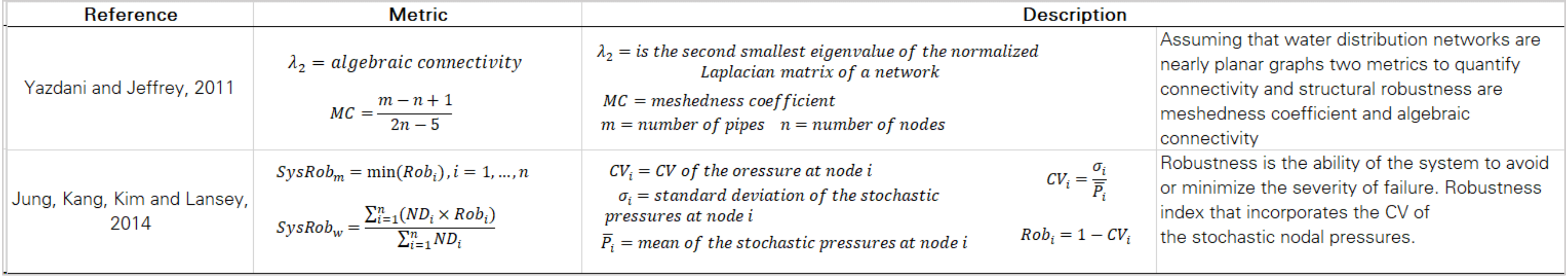
Table 2-1 Resiliency Metrics

Reference	Metric	Description	
Todini, 2000	$I_r = \frac{\sum_{i=1}^{n_n} q_i{}^*(h_i - h_i{}^*)}{\sum_{k=1}^{n_k} Q_k H_k + \sum_{j=1}^{n_p}(P_j/\gamma) - \sum_{i=1}^{n_n} q_i{}^* h_i{}^*}$	I_r = Resilience Index q_i = Flow at node i h_i = Head at node i H_k = Head for reservoir k Q_k = Discharge for reservoir k γ = Specific Weight P_j = Power introduced into the network by the j^{th} pump and n_p the number of pump n_k = Number of reservoirs n_n = Number of nodes $*$ Indicates the minimum required	Relates redundancy to the excess power (discharge*head*water specific weight) that can be delivered to each node when compared to the maximum power that would be dissipated internally in order to satisfy the constraints in terms of demand and head at the nodes.
Prasad and Park, 2004	$I_N = \frac{\sum_{j=1}^{n_n} C_j Q_j (H_j - H_j{}^l)}{\sum_{k=1}^{n_r} Q_k H_k + \sum_{l=1}^{n_p}(P_l/\gamma) - \sum_{j=1}^{n_n} Q_j H_j^*}$	Q_j = Discharge for node j Q_k = Discharge for reservoir k H_k = Head for reservoir k H_j = Head for node j P_j = Power introduced by pump l C_j = Uniformity coefficient for node j $C_j = \frac{\sum_{i=1}^{npj} D_i}{npj \times \max\{D_i\}}$ D_i = Diameter for pipe i npj = Number of pipes connected to node j	The resilience index at each node j is given a weight of Cj based on the uniformity in diameter of pipes connected to it. The network resilience index seeks to include the importance of loops.
Jayaram and Srinivasan, 2008	$MI_r = \frac{\sum_{i=1}^{n_n} Q_j{}^{req}(H_j - H_{\min j})}{\sum_{i=1}^{n_n} Q_j{}^{req} H_{\min j}} \times 100$	MI_r = Modified Resilience Index n_n = Number of nodes $Q_j{}^{req}$ = Required discharge for node j $H_j{}^{req}$ = Required head for node j Q_j = Discharge for node j H_j = Head for node j	Defined as the amount of surplus power (discharge*head*water specific weight) available at the demand nodes as a percentage of the sum of the minimum required power at the demand nodes. The metric intends to better reflect redundancy for networks with multiple sources.
Reed et al., 2009	$R = \frac{\int_{t_1}^{t_2} Q(t)\,dt}{(t_2 - t_1)}$	R = Resilience $Q(t)$ = Demand supplied at time t after the event t_1 and t_2 = Endpoints of interval under consideration	The method proposed evaluates the resilience of infrastructure networks under natural hazards (e.g., earthquakes and hurricanes) by comparing the demand supplied before and after the event.
Herrera et al., 2016	$I_{GT}(i) = \sum_{S=1}^{S}\left(\frac{1}{K}\sum_{K=1}^{K}\frac{1}{r(k,s)}\right)$	K = number of routes from the source and node S = Total number of sources in the network $r(k,s)$ = Surrogate mesuare of energy loss associated the k^{th} path for source s M = number of pipes in pipe k D_m = Diameter of pipe m L_m = Length of pipe m $r(k) = \sum_{m=1}^{M} f(m)\frac{L_m}{D_m}$ $f(m)$ = friction factor for pipe m	The metric uses the potential energy loss associated with each path connecting a node and its water source to estimate resilience.
Cimellaro et al., 2016	R=R1*R2*R3	$R_i = \int_0^{T_{LC}} \frac{F_i(t)}{T_{LC}} dt \quad i = 1,2,3$ T_{LC} = Control time $F_1(t) = 1 - \frac{\sum_i n_{p,e}^i}{n_{Tot}}$ $n_{p,e}^i$ = number of users at each node that suffer insufficient pressure n_{Tot} = total number of users within the distribution system $F_2(t) = \begin{cases} \frac{h(t)}{h_{Reserve}} & h \le h_{Reserve} \\ 1 & h > h_{Reserve} \end{cases}$ $h(t)$ = water level at time t $F_3(t) = \frac{Q(t)}{Q^*}$ Q^* = Water quality index before event $Q(t)$ = Water quality index after event	A resilience index (R) proposed by Cimellaro et al. (2016) for earthquake events summarizes the performance of a network by combining three indices, the demand (R1), the capacity (R2), and the water quality aspects of the network (R3).

Table 2-2 Redundancy Metrics

Reference	Metric	Description	
Cuadra et al., 2015; Gunawan et al., 2017	$C_i = \frac{2M_i}{k_i(k_i-1)}$	M_i = number of links that exist between k_i nodes k_i = number of links incident to node i C_i = Clustering coefficient	The clustering coefficient reflects the number of triangles in a network, each triangle is formed by two nodes connected to a third node that are also connected to each other.
Buhl et al., 2006	$M = \frac{m-n+1}{2n-5}$	M = Meshedness coefficient m = number of edges n = number of nodes	The meshedness coefficient characterizes the status of loops in the network using a ratio between the loops present in a network and the maximum possible number.
Awumah at al.,1991	$S_j = -\sum_{i=1}^{n(j)} \left(\frac{q_{ij}}{Q_j}\right) \ln\left(\frac{q_{ij}}{Q_j}\right)$	S_j = Redundancy at node j q_{ij} = flow carried by link between node i and j Q_j = Total flow at node j n_j = Number of links incident to node j	Entropy based measure. The metric favors equal distribution of flow, reducing the impact of each failing pipe
Sing and Oh, 2015	$S_j = \frac{K}{m-1}\left\{\sum_{i=1}^{n(j)}\left[\left(\frac{q_{ij}}{Q_j}\right) - \left(\frac{q_{ij}}{Q_j}\right)^m\right]\right\}$	S_j = Entropic measure of redundancy at node j m = entropy index $n(j)$ = Number of links incident to node j Q_j = Total flow at node j q_{ij} = flow carried by link between node i and j K = Positive constant (usually one)	Entropy based measure. The metric favors equal distribution of flow.
Kalungi & Tanyimboh, 2003	$T = \frac{R - r(0)p(0)}{1-p(0)}$	$R = \frac{1}{Q^{req}}\left(p(0)Q(0) + \sum_{l=1}^{NL} p(l)Q(l) + \sum_{\substack{l=1 \\ m=l+1}}^{NL-1} p(l,m)Q(l,m)\right)$ $+\frac{1}{2}\left(1 - p(0) - \sum_{l=1}^{NL} p(l) + \sum_{\substack{l=1 \\ m=l+1}}^{NL-1} p(l,m)\right)$ $p(l)$ = probability that only link l is unavailable $p(l,m)$ = probability that link l and m are unavailable $Q(0)$ = outflow when zero components are unavailable $Q(l)$ = outflow when link l is unavailable $Q(l,m)$ = outflow when link l and m are unavailable NL = number of links $r(0)$ = ratio of available flow to the required $p(0)$ = probability that no link is unavailable $p(0) = \prod_{l=1}^{NL} a_l$ a_l = probability a link l is available	The metric combines the results of a hydraulic simulation with the probability a links will be available in the network. The redundancy (T) takes a value between 0 (tree like system) and 1 (graph formed by triangular loops).
Dueñas-Osorio, Craig, Goodno, & Bostrom, 2007	$R_{Rv} = \frac{1}{(\lvert S\rvert - 1)^2}\sum I(v,j)$	$\lvert S\rvert$ = graph order, $\lvert S\rvert > 1$ – in graphs where every node has a link to every node $I(v,j)$ = number of node independent paths between nodes v and j	Originally intended for a power network, but has been adapted to other critical infrastructures. R_R= 0 indicates a fragment graph (the nodes are not connected to each other), R_R=1 every node has a link to every node.

Table 2-3 Robustness Metrics



Reference	Metric	Description	
Yazdani and Jeffrey, 2011	$\lambda_2 = algebraic\ connectivity$ $MC = \frac{m-n+1}{2n-5}$	$\lambda_2 = is\ the\ second\ smallest\ eigenvalue\ of\ the\ normalized\ Laplacian\ matrix\ of\ a\ network$ $MC = meshedness\ coefficient$ $m = number\ of\ pipes \quad n = number\ of\ nodes$	Assuming that water distribution networks are nearly planar graphs two metrics to quantify connectivity and structural robustness are meshedness coefficient and algebraic connectivity
Jung, Kang, Kim and Lansey, 2014	$SysRob_m = \min(Rob_i), i = 1, \ldots, n$ $SysRob_w = \frac{\sum_{i=1}^{n}(ND_i \times Rob_i)}{\sum_{i=1}^{n} ND_i}$	$CV_i = CV\ of\ the\ oressure\ at\ node\ i$ $\sigma_i = standard\ deviation\ of\ the\ stochastic\ pressures\ at\ node\ i$ $\overline{P}_i = mean\ of\ the\ stochastic\ pressures\ at\ node\ i$ $CV_i = \frac{\sigma_i}{\overline{P}_i}$ $Rob_i = 1 - CV_i$	Robustness is the ability of the system to avoid or minimize the severity of failure. Robustness index that incorporates the CV of the stochastic nodal pressures.

Table 2-4 Reliability Metrics

Reference	Metric	Description	
O. Fujiwara & De Silva, 1990	$R = 1 - \frac{Expected\ minimum\ shortfall\ in\ flow}{Total\ demand}$		Defines the system reliability as the ratio of the expected demand to the total demand.
Bao & Mays, 1990	$SysRel_m = \min(Rel_i), i = 1, \dots, n$ $SysRel_w = \frac{\sum_{i=1}^{n}(ND_i \times Rel_i)}{\sum_{i=1}^{n} ND_i}$ $SysRel_a = \frac{\sum_{i=1}^{n} Rel_i}{n}$	$Rel_i = hydraulic\ reliability\ at\ node\ i$ $Rel_i = \int_{P_{min}}^{\infty} f_i(P)dP$ $P_{min} = allowable\ minimum\ pressure$ $f_i(P) = probability\ density\ function\ of\ pressure\ P\ at\ node\ i$ $n = number\ of\ nodes$ $ND_i = demand\ at\ node\ i$ $SysRel_m = system\ reliability\ as\ the\ minimum\ nodal\ reliability$ $SysRel_w = system\ reliability\ as\ a\ weighted\ average$ $SysRel_a = system\ reliability\ as\ an\ arithmetic\ mean$	Three system reliability measures that are calculated from the nodal reliability: The minimum nodal reliability, arithmetic mean reliability, and nodal demand weighted mean reliability.
Gupta & Bhave, 1994	$R_{nw} = R_v F_t F_n$	$R_{nw} = Network\ reliability\ factor$ $R_{nj} = Node\ reliability\ factor$ $R_{nj} = \frac{\sum_s q_{js}^{avl} t_s}{\sum_s q_{js}^{req} t_s}\ for\ all\ nodes\ j$ $a_{js} \begin{cases} 1 & \frac{q_j^{avl}}{q_j^{req}} \geq Acceptable\ value\ defined \\ 0 & \frac{q_j^{avl}}{q_j^{req}} < Acceptable\ value\ defined \end{cases}$ $F_n = \left[\prod_{j=1}^{J} R_{nj}\right]^{1/J}$ $T = period\ of\ analysis\ (\sum t_s$ $J = total\ number\ of\ demand\ nodes$ $F_t = \frac{\sum_s \sum_j a_{js} t_s}{JT}$ $R_v = Volume\ reliability\ factor$ $t_s = time\ duration\ of\ a\ state(same\ for\ all\ nodes)$ $R_v = \frac{\sum_s \sum_j q_{js}{}^{avl} t_s}{\sum_s \sum_j q_{js}{}^{req} t_s}$ $q^{req} = required\ discharge\ rate$ $q^{avl} = available\ discharge\ rate$ $s = state\ subscript$ $j = node\ subscript$	The reliability metric proposed is based on a node-reliability factor, volume-reliability factor, and network reliability-reliability factor. This approach considers demands and the minimum head requirements (the head available at the node determines the discharge).
Xu & Goulter, 1999	$Rel_i = \int_{P_{min}}^{\infty} f_i(P)dP$	$Rel_i = hydraulic\ reliability\ at\ node\ i$ $P_{min} = allowable\ minimum\ pressure$ $f_i(P) = probability\ density\ functionof\ pressure\ P\ at\ node\ i$	Estimate the capacity reliability at a particular node L. The capacity reliability is closely related to hydraulic and demand variation failures (probability that the nodal demands meet the prescribed minimum).
Albert, Albert, & Nakarado, 2004;Poljanšek, Bono, & Gutiérrez, 2012;Fragiadakis, Christodoulou, & Vamvatsikos, 2013	$CL = 1 - \left\langle \frac{N_{s,j}^{dam.}}{N^{orig.}} \right\rangle$	$N_{s,j}^{orig.} = number\ of\ sources\ connected\ to\ node\ j\ before\ failure$ $N_{s,j}^{dam.} = number\ of\ sources\ connected\ to\ node\ j\ after\ failure$ $\langle\ \ \rangle = average\ of\ demand\ nodes\ J$	Connectivity Loss (CL) measures the average reduction in the ability od the demand nodes to receive floe from the source. More reliable networks would be able to provide pathways from the source to most of the nodes after failure

Table 2-5 Reliability Metrics (cont.)

Reference	Metric	Description	
Adachi & Ellingwood, 2008;Fragiadakis et al., 2013	$SR = \frac{\sum_j^N \omega_j X_j}{\sum_j^N \omega_j}$	$\omega_j = weighting\ factor\ for\ node\ \ j$ $X_j = 1\ or\ 0\ (node\ accesible\ to\ a\ source\ or\ not\ accesible)$ $N = number\ of\ nodes$	Serviceability Ratio (SR) was adapted for water distribution systems. SR is related to the number of nodes that can still receive supply from at least one of the sources after failure.
Cadini et al., 2010	$RE = \frac{1}{N(N-1)} \sum \frac{1}{d^{ij^r}}$	$N = number\ of\ nodes$ $d^{ij^r} = shortest\ path\ between\ nodes\ i\ and\ j$	Originally used for electrical networks. The metric uses the existing paths between nodes to define reliability. Higher values of RE reflect well connected nodes.
Dziedzic & Karney, 2015	$PI = \left[\prod_{m=1}^{M} P_m\right]^{\frac{1}{M}}$	$PI = Performance\ index$ $M = number\ of\ performance\ metrics$ $n = number\ of\ nodes$ $Q_{req} = Flow\ required$ $Q_{del\,p} = Flow\ delivered\ despite\ a\ pipe\ break$ $t = time\ step$ $h+1 = number\ of\ time\ steps$ $s = number\ of\ scenarios$ $i = scenarion\ (normal\ or\ failure)$ $E_{del} = Energy\ delivered\ to\ node$ $E_{sup} = Total\ energy\ supplied\ by\ oumps, tanks, gravitational\ flow$ $*\ indicates\ a\ failure\ condition$ $Reliability = \sum_{i=1}^{s} \sum_{t=0}^{n} \frac{E_{del\,t,i}/E_{sup\,t,i}}{(h+1)s}$ $Vulnerability = \min(E_{del\,t,i}, E_{sup\,t,i})$ $Connectivity = \min(Q_{del\,p}/Q_{req})$ $Resilience = \sum_{i*=1}^{s*} \sum_{t*=0}^{n*} \frac{E_{del\,t*,i*}/E_{sup\,t*,i*}}{(h^*+1)s^*}$	The energy-efficiency-based index is an aggregated metric taking the geometric average of the proposed performance metrics for: reliability, resilience, vulnerability and connectivity.PI ranges from 0 to 1, where 1 is the best possible performance.
Jung et al. , 2016	$SysRel_m = 0.0015LWAPD + 0.0465$ $SysRob_d = -2 \times 10^{-5} * TDS + 0.9976$ $SysRob_d = -0.0108AND + 0.0775MC$ $-3.2 \times 10^{-5} * TDS - 2.9 \times 10^{-5} * TSDS$ $+ 0.0002LWAPD$ $-1.5 \times 10^{-10} * TSA + 1.0060$	$AND = average\ node\ degree$ $NP_i = number\ of\ pipes\ connected\ to\ node\ i$ $AND = \frac{\sum_{i=1}^{n} NP_i}{n}$ $MC = meshedness\ coefficient$ $m = number\ of\ pipes\ \ n = number\ of\ nodes$ $MC = \frac{m-n+1}{2n-5}$ $TSDS = total\ system\ demand\ per\ source$ $NS = total\ number\ of\ fixed\ and\ variable\ head\ sources\ \ ND_i = demand\ at\ node\ i$ $TSDS = \frac{\sum_{i=1}^{n} ND_i}{NS}$ $LWAPD = length - weighted\ average\ pipe\ diameter$ $D_j = diamer\ of\ pipe\ j\ \ L_j = length\ of\ pipe$ $LWAPD = \frac{\sum_{j=1}^{m}(L_j \times D_j)}{\sum_{j=1}^{m} L_j}$ $TSD = total\ system\ demand\ \ TSA = total\ service\ area$	Univariate and multivariate linear reliability models developed by fitting a linear regression line to the scatter plots of the reliability measures and system characteristic indicators.
Sirsant & Reddy, 2020	$R = 1 - F$	$R = reliability\ of\ the\ system$ $F = failure\ probability\ of\ the\ system$ $F = \sum_{i=1}^{n_{seg}} P_{seg_i} \frac{D - S_{seg_i}}{D}$ $P_{seg_i} = the\ failure\ probability\ of\ segment\ i$ $D = the\ required\ demand\ for\ the\ entire\ WDN$ $S_{seg_i} = the\ actual\ supply\ to\ the\ WDN\ in\ case\ of\ failure\ of\ segment\ i$	Estimate of the mechanical reliability of the system considering valve location.

2.2 RELIABILITY in WATER DISTRIBUTION SYSTEMS

The question of reliability in water distribution systems and how to quantify it has been a pressing concern of the water industry. The design of reliable systems has been part of the criteria considered by engineers as they constructed and continued to operate the modern water distribution systems since the early twentieth century. However, to date there is no universally accepted definition for the reliability of a water distribution systems (see Table 2-5), although various metrics have been developed to estimate it throughout the years. In this document, reliability will be defined as the ability of the system to provide an acceptable level of service in face of a set of abnormal operating conditions or component failures (Cullinane et al. 1992).

This definition of reliability is thus dependent upon some type of failure-based approach or assessment. Thus, defining how water distribution systems can fail is necessary. At its most basic level, a water distribution system can be considered to fail, when it is no longer able to provide individual consumers with an adequate supply of water at acceptable pressures and water quality (Gheisi et al. 2016). Such failures are normally precipitated because of the physical or mechanical failure of system components (e.g. pumps, tanks, valves, and pipes) (Mays 1989). As a result, any failure experienced in a water distribution network could be grouped into two overarching mechanism affecting reliability: performance failure (i.e. network metrics fall below a specific design requirement) and component (mechanical) failure (i.e. an individual component is taken out of service) (Mays 1989; National Research Council 2006; Gheisi et al. 2016).

Although technically distinct, each failure mechanism may not necessarily occur independently, given that a triggering event could result in both types of failure. For instance, consider a pipe break due to excessive corrosion. This event is first a component failure. However, depending on the location of the pipe and the location of the valves required to isolate the pipe, this failure may cause a disconnection of a subsection of the network (i.e. topological failure) and in turn affect the flow delivered or pressures across the network (i.e. hydraulic failure). Depending on the time required to perform the necessary repairs and the location of the shutdown, the water supply could be left stagnant for an extended period. As the distribution systems acts as a reactor, the increased residence time in the lines could then affect the quality of the water delivered at the point of consumption, thereby leading to a water quality failure. The potential relationships between the mechanisms of failure and the impacts of such failures is summarized in Figure 2-1.

Table 2-6 Definition of reliability (from multiple sources)

Term	Definition	Reference
Reliability	Probability that a system will perform its mission within specified limits for a given period of time in a specified environment.	Gupta and Bhave (1994)
	Length of time that a system can be expected to perform without failure.	Mays (2000)
	Any measure of the system's ability to satisfy the requirements placed on it.	Mays (2000)
	The ability of the system to provide service with an acceptable level of interruption despite abnormal conditions.	Cullinane et al. (1992)
	The ability of a water distribution system to meet the demands that are placed on it where such demands are specified in terms of (1) the flows to be supplied (total volume and flow rate); and (2) the range of pressures at which those flows must be provided.	Goulter (1995)
	Refers to the probability that a given element remains functional at any given time.	Murray and Grubesic (2007)
	The probability that a system is in a satisfactory state, the probability that no failure occurs within a fixed period of time, reliability is one minus risk.	Hashimoto et al. (1982)

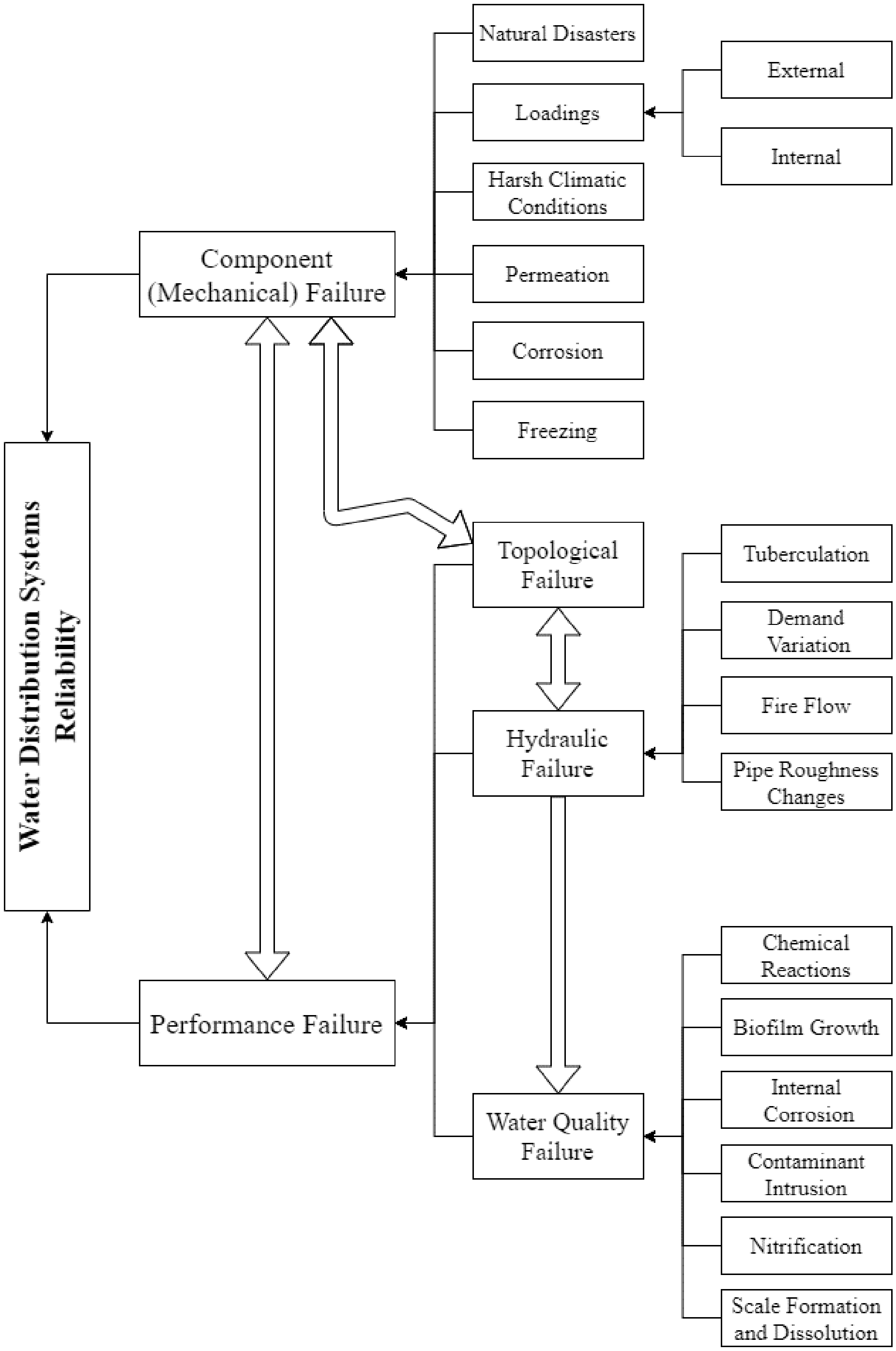


Figure 2-1 Mechanism of Failure and Reliability (Adapted from Gheisi et al 2016)

2.3 HYDRAULIC NETWORK SIMULATIONS

Examining the reliability of a water distribution network will often require determining the hydraulic behavior of the system, to accomplish this a computer model of the network coupled with a network simulator is used. All network simulators use the same core set of mathematical expressions to estimate the flows and pressures in a water distribution system: conservation of mass and conservation of energy equations. In most cases, the layout of the network and its components is represented as a series of links and junctions to which the equations are then applied. All pipes are considered as link elements while nodes may be junction nodes or fixed grade nodes. The junction nodes are used to model the mass balance of flows at the ends of individual pipes or at the intersection of multiple pipe links. While customer demands are withdrawn at various points along a pipe link, traditionally, the average demands are aggregated and then split equally and applied as point loads at each end of the pipe link at the associated junction nodes. On the other hand, tanks and reservoir are common fixed grade nodes since their pressure (or supply hydraulic grade) and elevation is fixed at an instant. Following this link-node representation of the system the conservation of mass for a junction can be expressed as equation (2-1)

$$\sum_i Q_{ij} = D_j \tag{2-1}$$

Where Q_{ij} is the flow in the link connecting i and j, and D_j is the demand at node j. Note, Qij is positive when the flow goes from i to j and negative when the flow goes from j to i.

Similarly, the conservation of energy for a pipe element ij can be expressed at equation (2-2).

$$H_i - H_j = aQ_{ij}\left|{Q_{ij}}^{b-1}\right| \tag{2-2}$$

Where H_i = the hydrostatic head at the upstream end of a pipe and H_j = the hydrostatic head at the downstream end of a pipe, and a and b are coefficients that are dependent upon the form of the equation used to characterize friction loss through a pipe. When the

Hazen-Williams equation is used for calculating headloss, $a = \frac{10.69L}{C^{1.85}d^{4.87}}$ (L is the pipe length [m], d is the pipe diameter [m] and C is a roughness coefficient), $b = 1.85$. If the Darcy-Weisbach equation is used for calculating headloss, then $a = \frac{8fL}{g\pi^2 d^5}$ and $b = 2$.

A more general expression for the conservation of energy along the path between any pair of nodes i and j, along a path of pipes l can be expressed as:

$$H_i - H_j = \sum_{all\ l \in path\ i-j} a\, Q_l \left|{Q_l}^{b-1}\right| \tag{2-3}$$

In a closed loop, one which begins and ends in the same node (i.e. $i = j$), the net energy loss is zero.

$$H_i - H_j = 0 \tag{2-4}$$

In the case of a path between two points with known total energy ΔE (e.g., reservoirs, tanks) can be expressed as:

$$Hi - Hj = \Delta E \tag{2-5}$$

Several different algorithms have been proposed for solving these equations, ranging from the Hardy Cross Method (Cross 1936), to the most recent method proposed by Todini and Pilati (1988). In each case, the nonlinear energy equations are represented by a first order Taylor's series approximation while allows the resulting set of algebraic equations are to be solved in an iterative fashion for either a vector of ΔH or ΔQ terms depending on the particular formulation of the energy equation. Upon convergence, the individual pipe flows Q and junction grades H can then be readily determined (Wood 1981; Boulos et al. 2006).

Table 2-7 Network Solution Methods

Reference	Method	Description	
Cross 1936	Hardy Cross Method (Single Loop Adjustment)	$\Delta Q = -\frac{\sum_{lloop} K_l \lvert Q_l \rvert^n}{\sum_{lloop} nKQ_l^{(n-1)}} = -\frac{\sum K \lvert Q \rvert^n}{\sum nKQ^{(n-1)}}$	The method solves the energy equations for loops and pseudo-loops for a loop flow correction.
Shamir & Howard 1968	Simultaneous Node Method	$\boxed{\begin{array}{c}\text{Matrix of node}\\ \text{terms [J X J]}\end{array}}\ \boxed{\begin{array}{c}\Delta H\\ \text{Is the}\\ \text{vector of nodal}\\ \text{head adjustments.}\end{array}} = \boxed{\begin{array}{c}-F(H)\\ \text{Loading Conditions}\end{array}}$	Using the node method requires the initial estimates of nodal hydraulic grade to be specified for each junction node.
Epp & Fowler 1970	Simultaneous Loop Equation Solution (Simultaneous Loop Flow Adjustment Algorithm)	$\boxed{\begin{array}{c}J_L(Q^{(m-1)})\\ J_L = dF/dQ^{(m-1)})\\ [(nloop+nploop)\\ \text{X}\\ (nloop+nploop)]\end{array}}\ \boxed{\begin{array}{c}\Delta Q\\ \text{Is the}\\ [(nloop+nploop)\ \text{X1}]\\ \text{vector of loop flow}\\ \text{corrections.}\end{array}} = \boxed{\begin{array}{c}-F(Q^{(m-1)})\\ \text{Is the } [(nloop+nploop)\\ \text{X}1]\text{ vector of residuals of}\\ \text{the loop conservation of}\\ \text{energy}\end{array}}$	The method simultaneously compute corrections for all loops. A system of linear equation must now be iteratively solved rather than a single equation.
Wood & Charles 1972,Wood 1976, Wood & Rayes 1981	Simultaneous Pipe Method	$\boxed{\begin{array}{c}\text{Matrix of Q terms}\\ \text{and pipe terms [n X}\\ \text{n]}\\ \\ \textit{Continuity Equations}\\ \textit{Populated by 1's and}\\ \textit{0's}\\ \\ \textit{Linearized Loop}\\ \textit{Equations}\end{array}}\ \boxed{\begin{array}{c}Q\\ \text{Is the [n}\\ \text{X1] vector}\\ \text{of flows.}\end{array}} = \boxed{\begin{array}{c}-F(Q)\\ \text{Loading Conditions}\\ \\ \textit{External Demands from}\\ \textit{Continuity Equations}\\ \\ \textit{Energy change through}\\ \textit{loop (for closed}\\ \textit{loops} \rightarrow 0)\end{array}}$	The method used the loop equations to represent conservation of energy. The linear theory was developed by coupling the loop and node equations.
Todini & Pilati 1987	Simultaneous Network Method/Solution of the Pipe Equations	$\begin{bmatrix} nA_{11} & A_{12} \\ A_{21} & 0 \end{bmatrix}\begin{bmatrix} \Delta Q \\ \Delta H \end{bmatrix} = \begin{bmatrix} -dE \\ -dq \end{bmatrix}$ $H^{(m)} = H^{(m-1)} + \Delta H^{(m)}$ $Q^{(m)} = Q^{(m-1)} + \Delta Q^{(m)}$ *Matrix A_{21} is the connectivity of topological matrix,* $A_{21} = A_{12}$ $A_{11} = \begin{bmatrix} K_1 \lvert Q_1 \rvert^{n-1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & K_{npipe} \lvert Q_{npipe} \rvert^{n-1} \end{bmatrix}$	The method writes conservation of energy for each pipe resulting in a set of npipe equations with *npipe* flows and the *nnode* nodal heads as unknowns. The equations are coupled with the node equations in terms of pipe flows to form a set of *npipe+nnode* equations and equal number of unknowns.

2.3.1 Extended Period Simulations

To evaluate the performance of a hydraulic network over time or perform a water quality analysis of a distribution system, an Extended Period Simulations (EPS) is required. An extended period simulation is used to incorporate the changes in customer demand and other boundary conditions for the system (e.g. water tank levels, pump discharge pressures, etc.) that change over time. In performing an extended period simulation of a water distribution system, the modeler sets the initial boundary conditions along with an incremental time step. The computer model is then used to perform a series of steady state simulations starting with an initial set of boundary conditions. The flows and pressures that result from this simulation are then used along with the incremental time step to forecast the boundary conditions at the end of the time increment. The computer model is then run with these new boundary conditions, forecasts are then made, new boundary conditions are established, and additional simulations are run until the entire simulation period has been analyzed. In most cases, the tank levels at the end of an incremental simulation period can be forecast using a simple Eulerian approximation, where for each storage tank (S) the change in storage can be expressed as,

$$\frac{dV_t}{dt} = Q_s \tag{2-6}$$

And

$$H_S = E_S + h(V_S) \tag{2-7}$$

Where V_t is the volume in the storage tank at time t, Q_S is the flow into (positive) or out of (negative) the tank, dt is the incremental time step, H_S is the hydraulic grade line (or water level) in the tank, E_S is the bottom elevation of the tank, h is water depth in the tank expressed as a function of the volume of water V_S is the tank. Once the extended period hydraulic simulation is completed, the incremental flows in each pipe link at time step can then be used as boundary conditions for use in predicting the travel times and associated water quality concentrations through a separate water quality simulation.

2.3.2 EPANET

EPANET is a public domain water distribution system modeling package developed by the U.S. Environmental Protection Agency Division of Water Supply and Water (Rossman 2000). The package can perform steady state and extended period simulations for hydraulic and evaluate water quality behavior in pressurized pipe networks. While the program first appeared in 1993, the last official version was published by EPA in 2008 (i.e. version 2.00.12). However, the program continues to be upgraded and refined through an open source project site in GitHub with the most recent release of EPANET 2.2 in 2020. All existing versions of the program can be downloaded through the official USEPA website (EPA 2017) or through the open source project site (https://github.com/USEPA/EPANET2.2).

The EPANET programing package includes a network solver module (based on the method of Todini and Pilati (1988) and a graphical user interface (GUI). The solver program can be executed independently using a text file as an input while the results file can be saved as a text file or a binary report file. The input processing, hydraulic analysis, water quality analysis, equation solver and the report generator are separated into modules (Figure 2) which facilitates potential modifications to the features of the program and computations.

In an effort to allow developers to customize EPANET to better fit their needs, a Programmer's Toolkit (Rossman 1999) has been developed that provides a library of routines which contain the different functions and algorithms of the network solver. These routines can be "called" from other software programs that can be used to: 1) open a network file; 2) read and modify the network and the associated operating parameters; 3) run simulations; and 4) set-up the results in a specified format. In this research effort, the components of the Programmer's Toolkit were modified to allow them to be repeatedly "called" from MATLAB which was then used to develop a series of segment identification, assessment, and valve placement optimization algorithms for use in fulfilling the objectives of the research. The resulting computational hierarchy is shown in Figure 3.

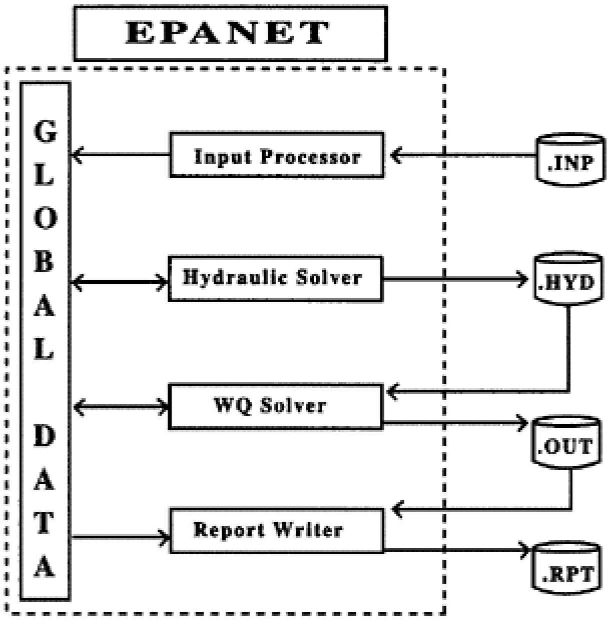


Figure 2-2 Data flow diagram for EPANET's solver (Rossman 2000)

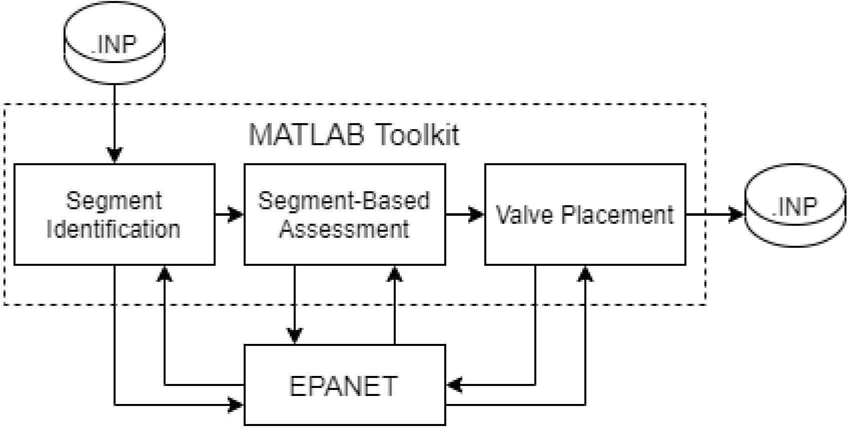


Figure 2-3 Computational Hierarchy Used in the Fulfilling the Proposed Research Objectives

2.4 OPTIMIZATION of WATER DISTRIBUTION SYSTEM

Hydraulic network simulators have been a valuable resource since their inception for the design and performance analysis of water distribution networks. However, these models alone cannot identify the most efficient design or the most advantageous rehabilitation strategy. When using hydraulic models alone, the designer relies on the iterative design process. Attempts to provide tools to assist in this process have resulted in a number of optimization approaches beginning in the 1970s and 1980s (Mays 1989; Mala-Jetmarova et al. 2017; 2018). These early optimization models focused on minimizing cost (i.e. investment and energy cost) while satisfying a given set of components constraints (e.g. available pipe diameters) and operational constraints (e.g. delivery pressures). Such research has resulted in an extensive number of methodologies and applications in the water distribution systems field (Savic et al. 2018).

Overall, regardless of the application, the conventional optimization problem for water distribution systems can be stated as a mathematical function(s) expressing the objective(s) to maximize or minimize, and a set of system constraints formulated as a function of the decision variables. For instance, take the general optimization formulation first presented by Ormsbee (1989) for cost minimization stated in terms pipe diameters, pump heads, and tank elevations (i.e. X) and nodal pressures

Objective: Minimize cost

$$f(X, H) \tag{2-8}$$

Subject to

Conservation of mass and energy

$$g(H, \hat{X}) = 0 \tag{2-9}$$

Head bounds

$$H_{min} < H < H_{max} \tag{2-10}$$

Design constraints (maximum and minimum allowed tank elevation)

$$h_{min}(x) < h(x) < h_{max}(x) \tag{2-11}$$

General constraints (other constraints on variables dependent on X and H, such as velocity)

$$v_{min}(H, x) < v(H, x) < v_{max}(H, x) \tag{2-12}$$

The constraints often involved in the optimization formulation involve the non-linear equations that define pressure and flow in the network under multiple loading conditions (i.e. $g\ (X, H)$). These constraints can frequently be de-coupled from the optimization algorithm and solved separately using an iterative coupling with a network simulation program such as EPANET once a minimum number of parameters has been set.

Although the minimum cost problem is the most addressed objective, a few other functions have been used in applying the optimization to a variety of problems. Other objectives used for the optimization algorithms as qualified by Mala-Jetmarova et al.

(2018) can be grouped under four types: economic, community, performance, and environmental. The optimization models with economic objectives address the capital cost of the system (Ostfeld 2005), the rehabilitation cost (Kim et al 1994), costs of repairs (Roshani and Filion 2014) and maintenance (Kang and Lansey 2013).The community-based objectives consider the service provided to the customers of the system. This type of optimization objective would include water quality (Fu et al. 2013), hydraulic performance (Fu et al. 2013; McClymont et al. 2014), fire flow deficit (Kanta et al. 2012), and welfare (Halhal and Savic 1999). Under this classification system performance encompasses robustness (Babayan et al. 2007), reliability (Creaco et al. 2014), and resilience (Basupi and Kapelan 2015). Finally, the environmental objectives represent the functions that address the emissions from manufacturing/installation of the system (Wu et al. 2010) and those from its operation (Roshani and Filion 2014).

Similarly, the constraints of the optimization model can be subdivided into hydraulic (extending water quality) constraints, system constraints, and constraints on the decision variable X or in the decision variable vector $\hat{X}$ (Mays 1989; Mala-Jetmarova et al. 2018). The hydraulic constraints consider the physical requirements of the distribution network: conservation of energy and mass (e.g. equation (2-9)), while the system constraints limit the operational requirements of the network (e.g. pressure bounds as in equation (2-10)) , the availability of the components or properties of the components themselves (e.g. design constrain (2-11) limiting the elevation of the water tank) and general constraints that are a function the hydraulic functions and the decision variables (e.g. equation (2-12) with constraints on allowable velocity). Other general constraints which could be placed on the decision variables could include limiting the pipe diameters to commercially available sizes (Filion and Jung 2010), limits on roughness coefficients bounds (Ormsbee 1989), limits on link lengths (Loganathan et al. 1995), or constraints that extend to other system components (e.g. pump size, tank volume).

In most optimization problems, sizing the pipe (e.g. diameter, length) is the main or only decision variable of choice (Alperovits and Shamir 1977; Ormsbee 1979; Kessler and Shamir 1989; Lansey and Mays 1989; Mays 1989; Mala-Jetmarova et al. 2018). However, several component parameters can be used to better fit the application of the optimization models. Some of the decision variables used in various models include pump locations (Vamvakeridou-Lyroudia et al. 2005), pump size (Ormsbee 1985; Lansey and Mays 1989), pump schedule (Ormsbee 1989; Fu et al. 2013), tank location (Dandy and Hewitson 2000), tank sizes (Prasad 2010),valve locations (Alperovits and Shamir 1977), valve settings (Lansey and Mays 1989), hydraulic head at junctions (Bragalli et al. 2012), nodal demands (Basupi and Kapelan 2015), and disinfectant dosage (Shokoohi et al. 2016), among others.

Once the optimization problem has been stated, a solution method is required. These methods can be defined as a deterministic, heuristic, or a hybrid (Mala-Jetmarova et al. 2018; Savic et al. 2018). These methods include formal optimization methods and trial and error techniques. The deterministic optimization methods use the analytical properties of the problem to generate a series of candidate solutions that seek a globally optimal solution. On the other hand, the metaheuristics approaches can be used to solve a variety of problems without requiring an exact expression, typically providing a good but not necessarily the globally optimal solution. Examples of some of the solution methods that have been used on water distribution system optimization are summarized by methodology type on Table 7.

Because of the non-linear nature of the conservation of energy equations that govern the hydraulics of the of water distribution systems it is often not possible to solve some problems guaranteeing a global optimum or a solution within a reasonable time limit (Mays 2000; Savic et al. 2018). Recognizing these constraints, optimization approaches have been applied to a variety of challenges in water distribution systems. Some examples include:

- Design. This generally involves determining the sizes and location of the components (i.e. pipes, pumps, tanks, and valves) for a new system while keeping the cost to a minimum. This type of application may also include multi-objective approaches that combine an economic objective (e.g. minimize cost) and a community or performance objective (e.g. maximize a benefit).
- Operation. In an existing system some operational schedules may be more economical than others while still providing an adequate service level.

Operational optimization seeks to minimize the economic objective while addressing two main areas: pump operation and water quality.

- Rehabilitation. This often refers to pipe replacement. The objective is to minimize the investment cost of the replacement components while prioritizing the critical elements. Some approaches will also consider how the level of service to customers is affected.
- Strengthening. In an existing system this will include the reinforcement of the network elements to meet future demands by adding parallel pipes.
- Expansion. This type of optimization task includes the design of a new section beyond the existing water distribution system while strengthening the existing infrastructure.
- Reliability, robustness, and resilience. The optimization model includes a system performance metric. Multiple approaches are used since there is no universal definition of these system properties.

It is noticeable that although reliability optimization approaches have been present in the literature since the early 1990s, the optimal placement of isolation valves has received limited attention. Although the use of isolation valves has been considered a practical option to improve the reliability of a water distribution system (Mays 2000; Ozger and Mays 2005), the use of rules of thumb continues to be the predominant practice. Some of the valve placement models have been suggested in literature are briefly summarized on Table 8. The framework proposed in this document seeks not only to evaluate the current level of reliability that the existing valve layout provides to a series of real water distribution networks but also to explore a simple heuristic approach to provide valve placement locations that could mitigate the consequences of a failure event in the future.

Table 2-8 Types of Optimization Models

Type	Description	Methods	References
Deterministic	The problem or system is well known. The method follows a strict mathematical approach to state the problem and find the solution. The optimal solution is guaranteed to be the global optimum (within a tolerance level). Uncertainty is not introduced.	Linear Programming (LP), Non-Linear Programming (NLP), Dynamic Programing (DP), and Mixed-Integer NLP (MINLP)	LP: Alperovits et al (1977),Ormsbee and Wood (1986) ,Kessler et al (1989) | NLP:Ormsbee (1985), Lansey et al (1989) | DP: Zessler and Shamir (1989) | MINLP: Kim et al (1994)
Metaheuristics	These methods involve some level of uncertainty or random components, they do not require linearization or a strict mathematical form. These algorithms usually borrow principles of physics, biology, and ethology. A global optimum solution is not guaranteed, but a quality solution can be found in a reasonable amount of time.	Genetic Algorithms (GA), Genetic Algorithm variants (CMBGA,ALCO-GA), Simulated Annealing (SA), Shuffled Frog Leaping Algorithm (SFLA), Shuffled Complex Evolution (SCE), Harmony Search (HS), Cuckoo-Search algorithm (CSHS), Particle Swarm Optimization (PSO), Scatter Search (SS), Immune Algorithm (IA), Memetic Algorithm (MA), Honey Bee Mating Optimization (HBMO), Differential Evolution (DE), NSGA-II, Evolutionary Algorithm (EA)	GA: Simpson et al (1994), Savic et al (1997), Wu et al (2002) | CMBGA: Zheng et al (2013) | ALCO-GA: Johns et al (2014) | SA: Costa et al (2000) | SFLA: Eusuff et al (2013) | SCE: Liong et al (2014) | HS: Geem (2006) | CSHS: Sheikholeslami et al (2016) | PSO: Suribabu et al (2006) | SS: Lin et al (2007) | IA: Chu et al (2008) | MA: Banos et al (2010) | HBMO: Mohan et al (2010) | DE: Zheng et al (2013) | NSGA-II: Artina et al (2012) | EA: Avila et al (2017)

Table 2-9 Valve Placement Optimization

Title	Description	Methods	References
Design of optimal water distribution systems	WDS design and operation with split pipes using linear programming. Valve location is inclined as a decision variable	Linear Programming	Alperovits and Shamir (1977)
Reliability Improvements in Design of Water Distribution Networks Recognizing Valve Location	Valves are initially assumed to be located at the end of each link in the network, intermediate valves are used as a decision variable and placed to subdivide pipes. The objective function is to minimize the maximum expected segment (in this case a fraction of a pipe) volume deficit.	Linear Programming	Bouchart and Goulter (1991)
Optimal Location of Control Valves in Pipe Networks Recognizing Valve Locations	Method searches for appropriate locations of control valves in a water supply network and their settings using a genetic algorithm to obtain a maximum leakage reduction.	Genetic Algorithm	Reis et al (1997)
Optimal location of isolation valves in water distribution systems: a reliability/optimization approach	A random junction is chosen, and valves are added to the valve-less pipes around that junction. Next a random pipe around the same junction is removed if it is different than the pipes where valves where just added. The optimization method maintains the “one less valve” constraint as long as the next solution is feasible.	Simulated Annealing	Ozger and Mays (2005)

Optimal Placement of Isolation Valves in Water Distribution Systems Based on Valve Cost and Weighted Average Demand Shortfall	A multi-objective genetic algorithm is used instead to search for the optimal position of the valves. In the application of the method different objective functions were used and compared to solve the problem as to the optimal placement of the valves. The results showed that the most appropriate ones are the total cost of the valves (to be minimized) and the weighted average "water demand shortfall" (likewise to be minimized)	Genetic Algorithm	Creaco et al. (2010)
Identification of segments and optimal isolation valve system design in water distribution networks	The isolation valve system is designed using a classical multi-objective optimization using genetic algorithm. Minimizing demand shortfall.	Genetic Algorithm	Giustolisi and Savic (2010)
Optimal Water Distribution Network Design Accounting for Valve Shutdowns	Presents a strategy for optimal design accounting for mechanical reliability with respect to pipe failures, i.e., accounting for the actual isolation valve system and network configurations generated because of valve shutdowns. The optimization considers mechanical reliability and cost.	Optimized multi-objective genetic algorithm (OPTIMOGA)	Giustolisi et al. (2014)
Upgrading Reliability of Water Distribution Networks Recognizing Valve Locations	An iterative procedure for upgrading water distribution network reliability is proposed by recognizing valve locations. In each iteration, three types of alternatives: (1) an addition of a valve(s) to pipe(s) without a valve; (2) an addition of a parallel pipe to an existing pipe; and (3) an	Heuristic	Gupta et al. (2014)

	increase in size of newly added pipes, are compared and the best is implemented.		
Improving Water Distribution Systems Robustness through Optimal Valve Installation	The optimal valve locations and the number of additional valves is determined by pipe failure analysis through the trade-off relationship with the number of additional valves and the maximum damage under pipe failure situations.	Weighted utopian approach	Choi et al. (2018)
Water Distribution Network Reliability Assessment and Isolation Valve System.	The optimal design for isolation valves balances maximizing the WDN-modularity index (IVS) and the minimizing the number of conceptual cuts.	Optimized multi-objective genetic algorithm (OPTIMOGA)	Giustolisi (2020)

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CHAPTER 3. SEGMENT IDENTIFICATION PROCEDURE FOR WATER DISTRIBUTION SYSTEMS

3.1 ABSTRACT

Isolation valves are a fundamental element of water distribution systems since they provide the ability to disconnect sections of the network, which is essential to address routine maintenance and emergency conditions. However, in most network reliability or resilience assessments valves are frequently not considered. Instead, such assessments are typically made assuming that each individual pipe can be isolated and taken out of service. This single link isolation approach assumes that all pipes have operable isolation valves at both ends of each pipe, which is neither realistic nor practical for most systems. In order to have a more accurate assessment of the distribution network and consider the role of valves, reliability and resilience assessment methods based on *segments* (i.e., the smallest set of pipes that can be isolated by the available valves in the distribution network) should be favored. This chapter presents a general procedure which uses a standard EPANET network file structure to identify such *segments*, their elements, and unintended isolations resulting from shutdowns. This procedure is then tested on a set of real water distribution networks.

3.2 INTRODUCTION

The term *segment* was first introduced in the context of water distribution reliability assessment by Walski (1993) who used it to describe the smallest set of pipes that can be isolated by the closest available isolation valves. Segments represent more accurately the number and spatial distribution of the elements taken out of service when a component failure needs to be addressed. Once a pipe break occurs or a repair becomes necessary, system operators require operable isolation valves to close a subsection of the network. Using a segment-based method in place of a single link shutdown provides for a way to consider the neighboring pipes that will also be taken out of service by considering how the spatial layout of the isolation valves will allow for the isolation of the failed component (Figure 3-1). The location of each isolation valve will ultimately define the impact of a given pipe break or component repair since each valve will act as the physical boundary separating the remainder of the network from the area of the incident.

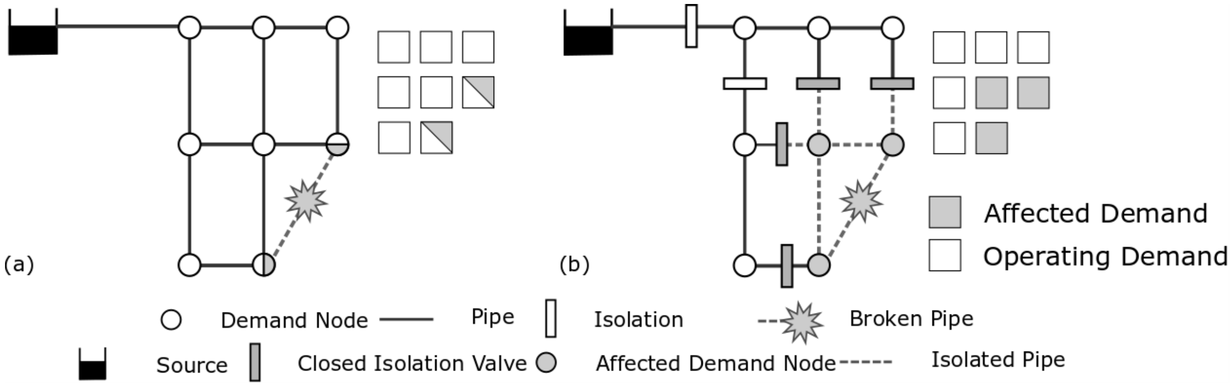

Figure 3-1(a) Single link failure compared to (b) segment failure caused by the same pipe breakage

While the importance of pipe segments in the context of system reliability is gaining increased attention by the water distribution research community, the importance of valves as elements to increase reliability has been historically recognized. Therefore, methods to optimize valve placement and improve valve performance have been previously proposed by various researchers (Reis et al. 1997; Ozger and Mays 2005; Creaco et al. 2010; Giustolisi and Savic 2010; Gupta et al. 2014; Choi et al. 2018). Nonetheless, in practice, valve placement is often guided by rules of thumb; such as installing one less valve as the number of intersecting legs of pipes at a junction (i.e., N-1 valves, where N = the number of intersecting legs of pipes) (Mays 2000). Other recommendations such as the Ten State Standards (GLUMRB 2012) suggests placing isolation valves at no more than 500 ft (150 m) intervals in commercial areas and at no more than 800 ft (240 m) in the rest of the system; while in areas with widely scattered customers it suggests valve intervals should not exceed a mile (1600 m).

In his original paper defining pipe segments in the context of valve placement, Walski (1993) proposed a graphical representation of valves and segments using a node-arc configuration where the segments were represented as nodes and the valves were represented as arcs (Figure 3-2). Such a representation provides a better way to illustrate the network since it provides a useful visualization of the number of valves required per segments and how the segments are connected among them. This representation has been adopted by several researchers (Loganathan and Jun 2007; Kao and Li 2008), as it facilitates the identification of unintended isolation and segment failure spillover in case of a valve malfunction.

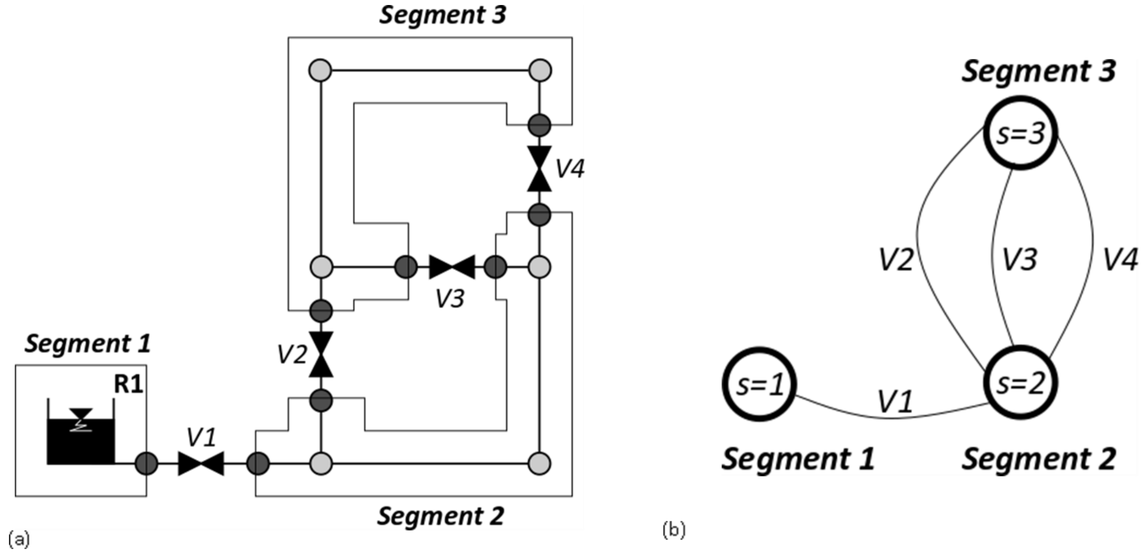

Figure 3-2 Two-loop network shown using a (a) Link-Node representation and (b) Arc-Node topology

One of the first authors to develop a node-arc identification algorithm was Loganathan and Jun (2007) who proposed the use of three matrices in representing the connectivity of the elements in a water distribution system as part of their segment identification procedure. These included a matrix to represent: 1) how elements are connected to each other, 2) the locations of the isolation valves and 3) a valve deficiency matrix. The valve location matrix was constructed by placing the isolation valves next to the closest junction relative to their location on the pipe or next to an artificial node for intermediate valves and representing it as such in their valve location matrix. This type of valve representation requires some transformation of the original data file topology used in EPANET (Rossman 2000). On the other hand, later segment identification algorithms, such as those proposed by Giustolisi and Savic (2010) have relied on the use of matrix computations in place of depth or breadth first algorithms. In this method the isolation valve locations are denoted by indicating the pipe where they are installed and the closest end node to the attachment. The topology of the network in this algorithm is then modified by representing the indicated valves as pseudo-links in a network adjacency matrix. Other methods proposed have avoided introducing new links. For instance, the algorithm introduced by Alvisi et al. (2011) stores the location of the isolation valves in an auxiliary matrix for pipes with a single valve attachment. It then uses an auxiliary vector for pipes with two isolation valves. Thus, this method maintains the topologic incidence matrix of the network so that no temporary links are created.

In the approach proposed by the author in this chapter, the segment identification procedure takes advantage of the existing EPANET network file structure where isolation valves have already been included. Thus, there is no additional processing of the network to create temporary fictional elements. EPANET users frequently model isolation valves using throttle control valves (TCV) since they tend to be more stable than other control elements available. However, this means that each isolation valve in the network model is represented as a link bounded by two nodes to be consistent with EPANET file formatting. Although this representation subdivides each pipe into several links, it accurately maintains the location of the isolation elements using links already in the topology instead of pseudo-links.

Beyond identifying the segments in the network, another central component of segment identification procedure includes determining if other parts of the network may become disconnected as the result of the loss of a given segment. Loganathan and Jun (2007) presented an additional algorithm for use in identifying unintended isolations that takes advantage of the arc-node representation. The algorithm uses a segment-valve connectivity matrix along with a breadth-first search algorithm to define the path between the available sources and segment-nodes for each individual segment-node failure or elimination. The algorithm produces a list of all node-segments that remain connected to a source after the removal of a segment. Any additional unintended isolations are those segment-nodes that are not included on the list of segment-nodes connected to a source. This procedure of segment removal, identification of connected segment nodes, and revision of unintended segment isolations is repeated for all identified segments by removing them one by one from the system.

Similar to Loganathan and Jun (2007); Kao and Li (2008) also make use of a depth-first search algorithm for segment identification but in their case they first convert the network topology into a node-arc representation as proposed by Walski (1993). In addition to being able to identify the complete set of valve isolation segments, Kao and Li (2008) also present an algorithm that can be used to identify all "critical" segments (i.e. those that create secondary isolations). Alternatively, the methods to identify secondary isolations proposed by Giustolisi and Savic (2010) or Alvisi et al. (2011) perform the task of identifying unintended isolations through simplified hydraulic system equations. In these cases the researchers rewrite the hydraulic simulation model of Todini and Pilati (1988) to pinpoint the unintended disconnections in the system in place of computing the hydraulic unknows in the system.

In the current chapter a procedure similar to that of Loganathan and Jun (2007) is employed for identifying secondary isolations, however it departs from their method in the way that it employs a segment-segment connectivity matrix. A similar segment-segment matrix is used by Gao (2014) in conjunction with a shortest path algorithm to compute transitive closures with good results in large networks, yet for this method the author uses a segment-segment adjacency matrix with a recursive search procedure. In general the method relies on the use of a topological adjacency matrix and breadth first search algorithms, with the objective of providing a method that can be easily replicated by users familiar with the EPANET environment and some introductory knowledge of the EPANET programmer's toolkit or the EPANET-MATLAB toolkit (Eliades et al. 2016). As a result, it is expected that the proposed approach will provide greater access to modelers in need of such tools, and lead to more applications in the area of network reliability and resilience.

In the following sections, a procedure is proposed by the author for use in identifying the existing valve isolation segments in a water distribution system using a standard EPANET network model file (i.e. INP). The algorithm described in the following sections was developed in MATLAB making use of the EPANET Toolkit to interact with the network input file. The list of the identified segments can then be used at a later instance to perform a segment-based reliability assessment, evaluate performance, or serve as the basis for the improvement of the existing isolation valve layout in the network by the user (Chapter 4)

3.3 ISOLATION VALVE REPRESENTATION

Prior to automating the process of identifying potential isolation segments, individual isolation valves are first represented as a link using a standard EPANET valve representation protocol. The location of each isolation valve is represented by a throttle control valve (TCV) in the EPANET environment. In this case, each pipe with valves attached is subdivided into smaller links depending on the location of the isolation element to allow the placement of the valve links. Although this means that a single pipe will be subdivided into several links, this enables the user to designate the precise location of the valve (see Figure 3-3) along a pipeline. Each link representing an isolation valve is bound by an upstream node (e.g. V3_U) which is the start node for the link representing valve 3 and a downstream node (e.g. V3_D) which is the end node for the valve 3 link.

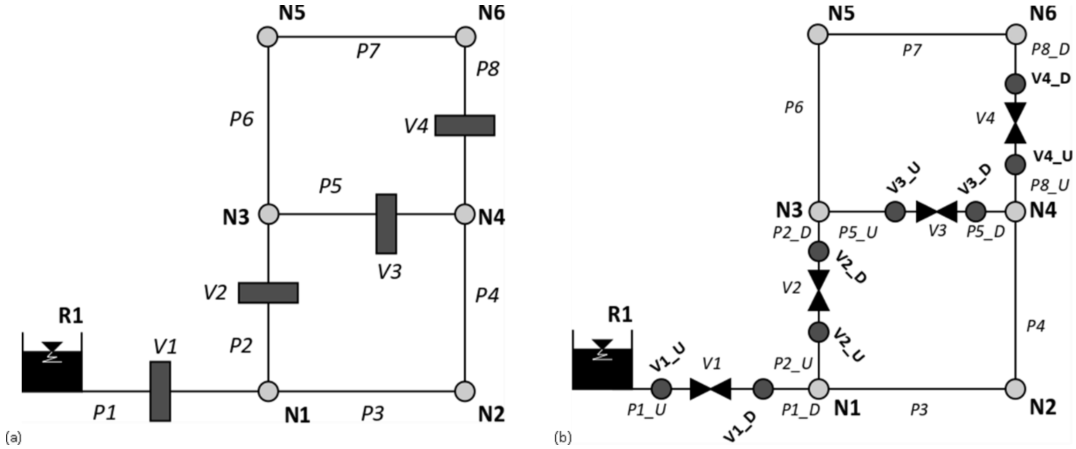

Figure 3-3 Simplified two loop System with (a) Isolation valves and then (b) represented using the EPANET topology, where R = reservoir, P= pipe link, N = junction node, and V= isolation valve

3.4 SEGMENT IDENTIFICATION

The segment identification method used in this methodology is initiated by representing the network in matrix form using a link-node incidence matrix or an adjacency matrix where the links (columns) are used to represents both pipe elements (i.e. P#) and valve elements (i.e. V#) and the nodes (rows) are used to represent both pipe nodes (i.e. N#) and valve nodes (i.e. V#_U,D). Recall that several pipe links can belong to the same pipe. Additionally, note that the source nodes such as tanks or reservoirs are represented as nodes (i.e., T# and R#). The N × L matrix, N rows for N node elements and L column for L link elements, is populated by zeros and ones; where each cell with a value of "1" indicates that a link with that row index is connected to a node with that column index and a value of "0" indicates the elements are not connected. This means if Node-1 is connected to Link-2 the cell at row one and column two will have a value of "1" (See Table 3-1)Each segment is then identified by traveling through the adjacent nodes and links of the matrix, i.e., moving across the rows and down the columns of the adjacency matrix using a four -step process.

Table 3-1 Adjacency Matrix for Two Loop System

		LINKS															
		P1_U	**V1**	P1_D	P2_U	**V2**	P2_D	P3	P4	P5_U	**V3**	P5_D	P7	P6	P8_U	**V4**	P8_D
NODES	R1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	V1_U	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	V1_D	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	N1	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0
	N2	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
	V2_U	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
	V2_D	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
	N3	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	0
	V3_U	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
	V3_D	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
	N4	0	0	0	0	0	0	0	1	0	0	1	0	0	1	0	0
	V4_U	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
	V4_D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
	N5	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
	N6	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1

Step One: Identify a Non-Valve Node That Has Not Been Visited to Begin the Search of a New Segment. To begin the process, the algorithm starts with the first non-valve ID it encounters in column 1 of the adjacency matrix (e.g. R1). From Figure 3-3 (b) it can be observed that the single source R1 is contained in Segment 1 which will include R1 and P1_U with V1_U as a boundary. Thus, for this example, we will start with the second *non-valve* node (i.e. N1) since it is the first junction node that is not a source or an isolation valve. Note in this case nodes V1_U and V1_D are isolation valve nodes, so they are skipped over as we move down the first column after starting with R1. Once a non-valve node is identified, the node ID (e.g. N1) is stored in the first row of the first column of an associated segment identification table (see Table 3-2).

Table 3-2 Segment Identification Table (S2)

Nodes	**Links**	**Valve Node**	**Valve Link**
N1			
	P1_D	V1_D	V1
	P2_U	V2_U	V2
	P3		
N2			
	P4		
N4			
	P5_D	V3_D	V3
	P8_U	V4_U	V4

Step Two: Identify a Link Associated with the Node That Has Not Been Visited. Once such a node has been identified, we now return to the adjacency matrix (see Table 3-1.) and beginning with the row containing node N1, the algorithm then moves right through each column looking for cells containing a value of 1 which would indicate that N1 is connected to those links. Once a link is identified, its ID (in this case P1_D) is then copied to the second row of second column after the row containing N1 (see Table 3-2).

Step Three: Identify the Node (Regular or Valve) on the other end of the Link. Once a pipe element or link (i.e. P1_D) associated with the current node (i.e. N1) is identified, the algorithm then starts at the top of that column in the adjacency matrix (i.e. the column associated with P1_D) then moves down the column until it encounters a cell with a 1. Once it encounters a 1 it then checks to see if the corresponding node in the ID column corresponds to the current starting node (i.e. N1) or an ending node (i.e. anything other than N1). If it is the starting node then the search continues down column 4 until it encounters an end node. If it is an end node, the algorithm then determines if the node is a regular junction node (i.e. N#) or a valve node (i.e. V#_U, D). If it is a regular node (e.g. N2), then the ID of the node is recorded in the line below the link (e.g. P3). If it is a valve node (e.g. V1_U), then the ID is recorded in the Valve Node column adjacent to the column containing the current link ID (e.g. P1_D). In this example, the first node encountered is a valve node (i.e. V1_D), which is placed adjacent to the Link ID in the Valve Node Column. Finally, the ID associated with that link, is placed in the Valve Link column (i.e. V1) as shown in Table 3-2.

Step Four: Identify the Next Link Connected to the Current Node. Once an end node for the first link has been identified and recorded in the segment ID table, the algorithm then returns to the row associated with the current node in the adjacency matrix, (i.e. N1) and then continues along that row in search of any additional pipe links. In this case, the next pipe link encountered is P2_U, at which point the link is recorded in the segment ID table and Step Three is then repeated for that link.

Continuing in this fashion, (repeating Steps Three and Four) for the current node (i.e. N1) results in the identification of two more links that are connected to the node (i.e. P2_D and P3). A search down the P2_U column yields another end point (i.e. V2_U) and its corresponding Valve Link ID (i.e. V2). A subsequent search down the P3 column encounters N1 (which is skipped since it is the beginning node) until it encounters a non-valve end node N2, which is recorded in the Nodes column in Table 3-2. At this point we have identified all links originating from node N1 and we are ready to move on to any additional nodes in segment 2 that have not yet been bounded. The next available node to examine is N2, which was just identified in the last iteration of Step Four. At this point we now repeat Steps Two through Four for that node.

A summary of those applications for the rest of the nodes and links in Segment 2 is provided as follows: Beginning a new row search on N2 leads to link P3 (which is now skipped because it has already been identified) and ultimately to P4. Beginning a new column search on P4 leads to N2 (which is now skipped because it is the beginning node in this search) leads to another non-valve end node N4, which is then recorded in the Nodes column in Table 3-2. as before. Continuing in this way will lead to the identification of two additional links (i.e. P5_D and P8_D) and their corresponding valve nodes (i.e. V3_D and V4_U) and valve links (V3 and V4), all of which are subsequently recorded in the segment ID table as shown in Table 3-2. This then ends the search of segment 2 since the row searchers of V3_D and V4_U fail to turn up any new links that have not already been visited.

Termination Criteria: One we have completed the search of the current segment and generated its associated segment identification table, we then return to Step 1 and look for a new non-valve node that has not been yet visited, which would be indicative of an unexamined segment. This process continues until there are no longer non-valve nodes that have not been visited. At this point, the algorithm ends.

3.5 SECONDARY ISOLATIONS

It should be recognized that the failure of an individual segment may also produce a series of additional unintended isolations. These unintended or secondary isolations can occur when the shutdown of the initial segment containing a pipe failure separates one or more additional segments from an available supply source (See Figure 3-4)

Two different scenarios are possible: (1) the supply source is external to the unintended isolation (Figure 3-4 (a)), and (2) a supply source is contained within the unintended isolation (Figure 3-4 (b)). When the supply source is contained within the unintended isolation, the impact of the original segment isolation will depend on the duration of the segment isolation and the volume and pressure supplied by the supply source. When the secondary isolation segment does not contain a secondary source, then service to that segment will also be lost. In the current segment identification methodology, the unintended isolations are simply those disconnected from any available source. However, in segment analysis it may be important to consider the effect on the pressure experienced across the network that remains connected. Several researchers have accommodated this consideration by incorporating a pressure dependent analysis to estimate undeliverable demands (Kao and li 2007; Giustolisi et al. 2008). In this chapter the intent is to first be able to identify the elements that are disconnected from any source as an unintended consequence of a primary isolation. Once the primary segment isolations have been identified, the secondary isolations can then be determined. Other work has examined the effect of the decreased pressures or resulting demands

3.6 SECONDARY ISOLATION IDENTIFICATION

Once a segment has been shut down, the secondary isolation identification algorithm first performs a search of the available paths from the remaining sources. The segments that cannot be reached when the search is completed are defined as the unintended isolations for the initial closure. This process employs three preparatory steps that are only performed once followed by nine recursive steps for each isolated segment. These are summarized as follows:

Preparatory Steps

Step One: Create a Segment Adjacency Matrix. The algorithm begins by creating a segment adjacency matrix which will be populated by cells with a value of 1 for adjacent segments or 0 for if the segments do not share at least one valve acting as a boundary between them (Table 3-3). This means that for the S segments identified, a $S \times S$ matrix will be constructed where if segment S1 is adjacent to segment S2 the matrix element in the row representing segment S1 will be assigned a value of 1 as well as the matrix element in the row for segment S2 and the column for segment S1.

Table 3-3 Segment Adjacency Matrix (Two Loop)

Segment	S1	S2	S3
S1	0	1	0
S2	1	0	1
S3	0	1	0

Step Two: Create a Segment Source Matrix. Next, a matrix is created that denotes the IDs of any tanks or reservoirs that are within each segment identified. The segment source matrix for the two-loop system in shown in Table 3-4. As can be seen from Table 3-4, isolation of segment S1 will result in the elimination of reservoir R1 while the isolation of segments S2 and S3 will not result in any source eliminations.

Table 3-4 Segment-Source Matrix

Segment	Reservoir	Tanks
S1	R1	0
S2	0	0
S3	0	0

Step Three: Create a Segment Source Availability Matrix. Once the segment source matrix is created, a segment source availability matrix is created. This matrix contains the list of source IDs that will remain available to the rest of the system when that segment is isolated and before secondary isolations are considered. This matrix is constructed by systematically removing each row, one at a time, in the segment source matrix corresponding with each segment, and then recording all of the remaining sources IDs left in the matrix by creating an array associated with that segment which contains the IDs of those sources. The resulting segment source availability matrix for the two-loop system is shown in Table 3-5. In theory, the number of source elements contained in each row could range from 0 to M, where M = the total number of sources in the network. In this example, since there is only one source for the whole system, the dimension of each row will be 1.

Table 3-5 Segment Source Availability Matrix

Segment	**Source 1**	**..**	**Source M**
S1	0	..	0
S2	R1	..	0
S3	R1	..	0

Iterative Steps:

Step One: Select a Primary Isolation Segment. The first step in the iterative search process is to select the first segment to isolate. This is done sequentially by simply iterating through the list of primary segments as identified the Segment Identification process. In this case, since isolation of segment S1 would isolate all segments, for illustrative purposes, we will start with segment S2. The shutdown of an individual segment *s* is shown in the Segment Adjacency Shutdown matrix by replacing the elements that had been assigned a value of 1 by 0 in row *s* and column *s*, since once the isolation valves surrounding the segment are closed segment *s* will be disconnected. For example, shutting down segment S2 in the two-loop example system will result in all cells in the row and the column associated with segment S2 being repopulated by zeroes (Table 3-6).

Table 3-6 Segment Adjacency Shutdown Matrix for S2

	S1	**S2**	**S3**
S1	0	0	0
S2	0	0	0
S3	0	0	0

Step Two: Identify Available Sources. Once an initial primary segment has been identified (e.g. segment S2) the algorithm then searches the row in the Segment Source Availability matrix associated with that ID for a remaining source ID (in this case R1). If no sources are found (Table 3-5), then this segment will isolate the entire network, and all other segment IDs are identified as secondary isolation segments, and the algorithm returns to Step One in search of another primary segment. If the algorithm does find a source, then it moves on to Step Three.

Step Three: Identify A Segment That Contains That Source. Once an available source has been identified, the algorithm next sequentially searchers the Segment Source matrix (Table 3-4), one row at a time, until it finds a segment that contains that source (i.e. S1 contains R1). Once a segment is identified, the algorithm goes on to Step Four. If no additional sources can be identified, then the algorithm goes on to Step Six.

Step Four: Identify Non-Isolated Segments. Once a remaining source and the segment connected to that source has been identified (i.e. R1 and S1), the algorithm then searchers along the row associated with that segment ID in the Segment Adjacency Shutdown matrix for the current primary segment S2 (i.e. Table 3-6) looking for cells with a value of 1. For each 1 that is encountered, the algorithm records the column ID associated with that cell in a "cumulative" Non-Isolated Segment (NIS) array, which stores all segments that will not be isolated from a source when the current primary segment (i.e. S2) becomes isolated. In the current example, there are no cells with a value of 1 in the row associated with segment S1, thus no new segments are added to the list and the algorithm goes on to Step Six.

Step Five: Initiate New Row Search for Each Adjacent Segment. If any adjacent segments are identified (as reflected by a value of 1 in the cell), a new row search is initiated for that segment (as identified in the column ID) in the Segment Adjacency Shutdown matrix (i.e. Table 6). This means that each of the rows corresponding to the segments identified as being adjacent to the source is now searched for other cells with a value of 1. The IDs associated with the columns of these new segments are now also added to the Non-Isolated Segment array if they have not already been enumerated. This row search/segment ID recording process is repeated until no more new segment IDs can be added to the array.

Step Six: Check Other Sources Available to Begin a New Search. Once no additional segments IDs are identified (i.e. by virtue of having a 1 in the corresponding cell) that can be added to the Non-Isolated Segment Array for the current row (i.e. segment S1 associated with source R1), the algorithm then continues to search along the current row in the Segment Source Availability matrix (i.e. the row associated with segment ID S2 in Table 5) looking for any remaining source IDs. If any **new** source IDs are discovered, then the algorithm takes that ID and returns to Step Three. If no new sources are identified, then the algorithm continues to Step Seven.

Step Seven: Determine the IDs of the Secondary Isolated Segments for a Given Primary Segment. Once all sources have been exhausted for a given primary isolated segment, an array of all segments that will not be isolated as secondary isolations will now be contained in the Non-Isolated Segment Array associated with the primary segment ID. A list of segments that will be isolated as secondary segments can now be constructed by beginning with a list (or an array) of all the segments (excluding the primary segment) and then eliminating those segments that appear in the NIS array. These IDs will then be used to populate an Isolated Segment array for that primary segment ID (i.e. IA(ID)). Thus, for this example problem: IA(S2) = {S1, S3}.

Step Eight: Eliminate Any Segments Connected to Sources

Once the IA(ID) array is finalized, the algorithm then double-checks each element of the array against the Segment Source Availability matrix to make sure that none of the elements in the array has a connecting source. If one of the elements does have a source, then that element is eliminated from the array. For our example, the final array associated with primary segment S2 will look like this: IA(S2) = {S3} since segment S1 is connected to the source R1.

Step Nine: Check for Termination. Once the final array for a primary segment has been completed, the algorithm returns to Step One in search of the next primary isolated segment. Once all the segments have been examined, the algorithm ends along with a matrix of all the secondary isolated segment IDs associated with each primary segment. After all the individual segments and the accompanying secondary isolations have been found one now has sufficient data to launch a full segment reliability assessment.

3.7 APPLICATION

3.7.1 Case Studies

Thus far, the segment identification algorithm has been illustrated using a very simple two-loop network to facilitate a description of the algorithm. In order to illustrate the utility of the method for larger systems, the algorithm was applied to nine real-world distribution systems in the state of Kentucky drawn from the University of Kentucky Water Distribution System Research Database (https://uknowledge.uky.edu/wdsrd/ Accessed: August 14 2020) as originally documented by Hernandez et al, (2016). A list of the systems and their characteristics is provided in Table 3-7.

Table 3-7 Description of Systems Used to Validate the Proposed Segment ID Algorithm

Name of System	Valves	Links	Junction Nodes	Number of Segments	Number of Sources
KY6	346	1504	1406	255	5
KY8	488	2729	2446	294	7
KY18	465	1831	1692	344	3
KY19	167	834	811	152	15
KY20	48	249	212	23	2
KY21	204	853	801	157	12
KY22	96	633	595	68	8
KY23	441	2410	2339	378	15
KY24	43	206	204	41	2

3.7.2 Computational Results

The proposed segment identification and secondary isolation algorithms were executed within the MATLAB 2018b environment, implementing functions from the EPANET-MATLAB toolkit (Eliades et al. 2016), and run using an Intel Core i7-770 CPU with a frequency of 3.60 GHz. The computational requirements (in seconds) required to identify the primary and secondary isolated segments when applied to each of the nine systems are summarized in Table 8. The reported times required for segment identification (Seg. ID Time) includes the time required to define the total number of segments in a network and the time to identify the individual link and node elements that form each segment, as well as all the isolations valves. The isolation valves can be further subdivided into two different sets: the isolation valves that are completely contained within a segment (i.e. internal valves), and those valves that effectively close each section (i.e. external valves).

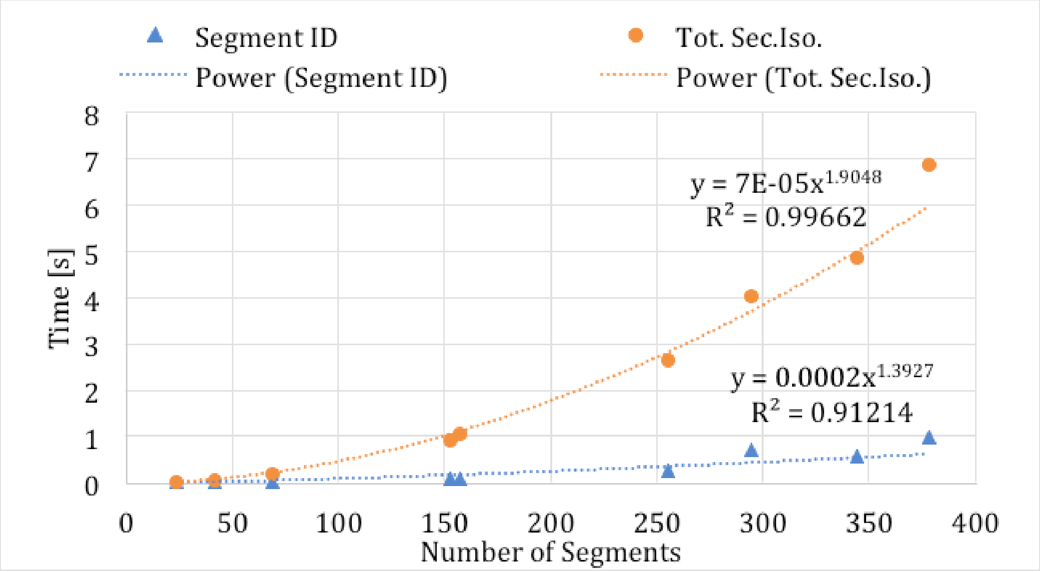

Figure 3-4 Comparison of Computation Times for Primary and Secondary Segment Identification

The two reported times required for identification of the secondary isolated segments (Total Secondary ID Isolation Time and Average Secondary ID Isolation Time) are associated with the total time to identify all of the secondary isolated segments and the average time required to identity an individual secondary segment respectively (see columns 4 and 5 in Table 8). To provide a relative baseline from which to compare the computational times, the computational times required to perform a normal steady state analysis and a single day 24-hour extended period simulation (EPS) using a 1-hour time step are also included in the table. In addition, a plot of the total computational times required to identify the primary and secondary segments as a function of the number of segments is provided in Figure 3-4. As can be seen from the results on Table 3-8 and Figure 3-4, the time to identify the secondary isolated segments is significantly longer than the time to identify the primary isolations (ranging from 1.5 to nearly 11 times the computational times). The longer total computation times required to identify the secondary isolations are linked to the recursive nature of the algorithm used to identify them. As discussed previously, the secondary isolations are identified by first locating all of the available sources following the shutdown of each segment, and then recursively enumerating all of the remaining connected segments. Theoretically, this recursive search could be repeated S x M times, where S = the total number of segments, and M = the total number of sources. Thus the total computational time to identify all of the secondary isolations will be dependent upon both of those parameters. Other factors that were also found to impact the times are the presence and number of long-branch segments that can be isolated by a single loop segment closure or the presence of redundant non-isolated segments associated with different sources.

Table 3-8 Computational Statistics for Each Tested Network

Name of System	Number of Segments	Segment ID Time [s]	Total Secondary Isolation ID Time [s]	Average Secondary Isolation ID Time [s]	Static Simulations Time [s]	EPS Simulation Time [s]
KY6	255	0.2775	2.669	0.01047	0.00611	0.0781
KY8	294	0.7389	4.069	0.01384	0.01350	0.1142
KY18	344	0.6054	4.902	0.01425	0.00835	0.2386
KY19	152	0.1102	0.935	0.00615	0.00614	0.0196
KY20	23	0.0220	0.035	0.00151	0.00212	0.0032
KY21	157	0.1023	1.082	0.00689	0.00299	0.0810
KY22	68	0.0533	0.221	0.00325	0.00397	0.0765
KY23	378	1.0173	6.917	0.01830	0.01120	0.2999
KY24	41	0.0232	0.077	0.00187	0.00263	0.0475

The ratios of the times to identify the primary segments versus the times to perform a steady-state analysis of the corresponding systems range from approximately 8 to 90 while the times to identify the secondary segments versus the times to perform an EPS analyses of the corresponding systems range from approximately 2 to 28. While the segment identification times are obviously significantly higher (in some cases nearly an order of magnitude), they do not seem unreasonable in relative comparison. Indeed the longest combined time (for both primary and secondary isolation identification) for one of the largest systems (i.e. KY23) is still less than 8 seconds. This is for a system with 2410 pipes, 2339 junction nodes, 441 valves, 378 segments, and 15 sources. Thus the algorithm seems to be able to identify both types of segments in a relatively short period of time.

Some idea of the potential computational times required for larger systems can be inferred by fitting a curve through the computational times of all of the examined systems expressed as a function of the number of segments (see Figure 3-4). Based on these relationships, the expected computational times to generate the primary and secondary segments associated with a system with 1,000 segments are only 3 seconds and 36 seconds respectively. Times to generate primary and secondary segments associated with a system with 10,000 segments are still only 1.2 minutes and 48 minutes respectively, thus showing the algorithm is still computationally feasible.

3.7.3 Example Application

In order to illustrate how the identified segments can be used in a reliability assessment and how such an assessment gives a more realistic appraisal of demand loss when considering the actual valves in a system, three of the networks (i.e. KY6, KY8, and KY 18) were used to simulate a series of both single element and segment failures. Schematics of each of the systems are provided in Figure 3-5

In performing single pipe isolation analyses for each network, the impact of each single pipe failure was quantified by simply removing the demands associated with the service connections with each line. For this analysis, this was approximated by removing one-half of that associated demand from each of the associated junction nodes to which that pipe element was attached. A ranking of the top ten most impactful pipes relative to the decrease of the total system demand is shown in Figure 3-6 (a to c). Notice, that in some cases, the isolation of a single pipe leads to other secondary isolations (and loss of demand) as in the case where isolation of a single pipe may lead to the isolation of several other pipes downstream in an extended branch.

In performing segment isolation analyses for each network, the impact of each segment failure was quantified by aggregating the expected demand from the portions of the network that were physically disconnected from the available sources. Given that these examples seek to compare the relative order of the most critical segment failures, the author has simplified the analysis by ignoring any shortages in supply due to possible decreases in system pressures. This means the failure simulations will only use the shortage in demand associated with the disconnected elements of the network (i.e. both primary and secondary isolations). This type of supply deficiency metric is often referred to as a topological metric (Creaco et. al 2012).

A ranking of the top ten most impactful segments relative to the decrease in total demand is shown in Figure 3-6 (d to f). Each segment histogram is further divided to illustrate the relative contribution of the primary and secondary isolations on the total demand loss. The number of valves need to close each segment is also noted at the top of each of the segment histograms.

Several things are immediately apparent from the figures. First, an assumption that the supply impact of single pipe failures can be modeled by only isolating the single pipe can significantly underestimate the magnitude of the impact. In fact, an examination of Figure 3-6 (a – c) shows that in most cases, the largest demand loss is associated with secondary isolations (e.g. when one pipe isolates an extended branch). Second, a consideration of the impact of the actual valves in a system can lead to a significant increase in the estimated total loss of supplied demand, even without a more detailed consideration of additional potential losses due to decreased system pressures. These finding further enforce the reasoning of other authors (Kao and li 2007; Giustolisi and Savic 2010; Creaco et al. 2012; Gupta et al. 2014) who have also argued for a consideration of valves and segments when performing reliability assessments. Third, it is worth noting, that in many cases, the impacts of the secondary isolations are greater than the losses associated with the primary isolation, thus highlighting the need for the identification of secondary isolations. Finally, while the number of valves needed to close a segment tends to correlate with the relative impact of that segment (i.e. Figure 3-6(d – f)) this trend is not universal, and thus reflects the impact of other secondary factors.

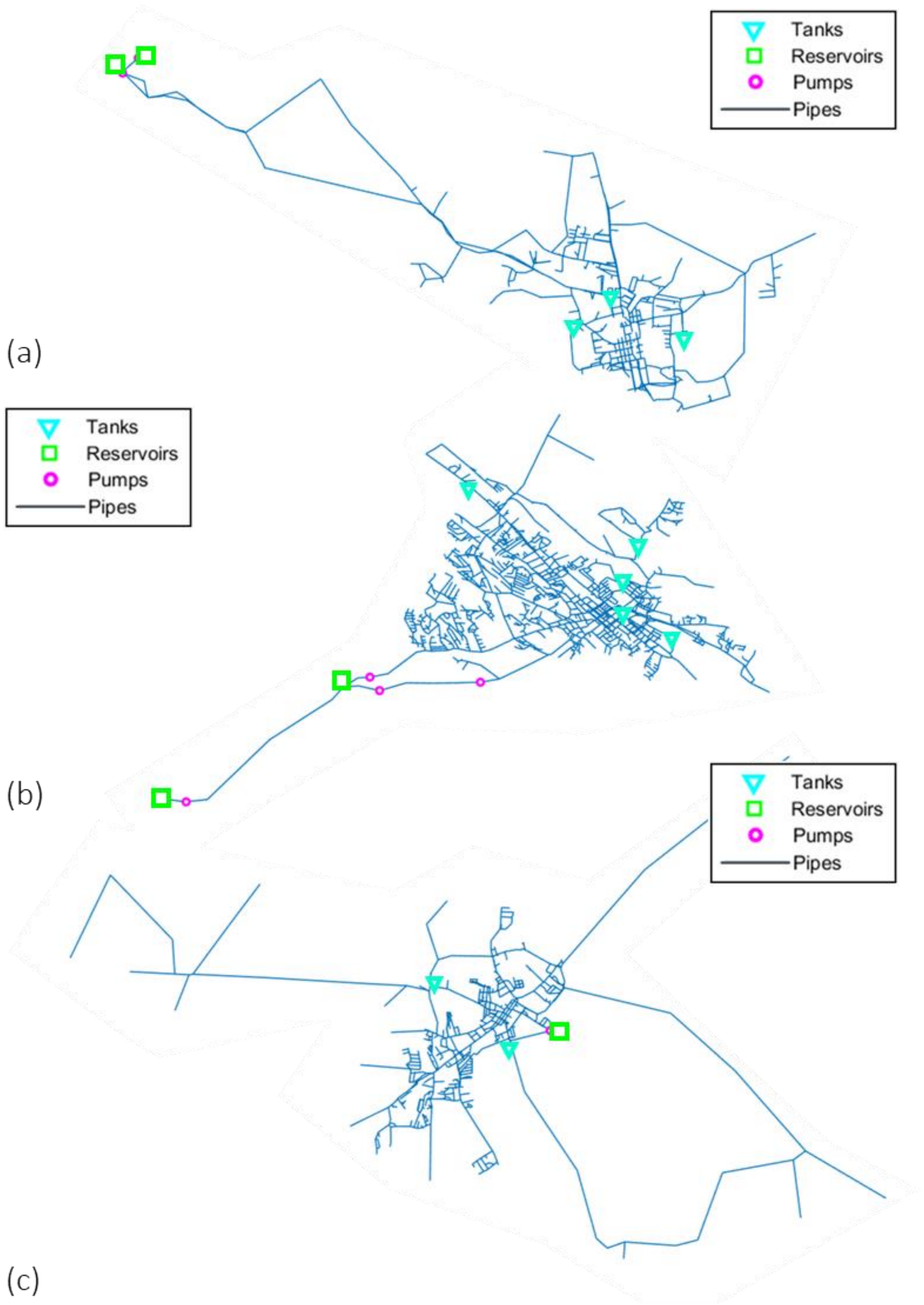

Figure 3-5 Network Schematics for KY6 (a), KY8 (b), and KY18 (c)

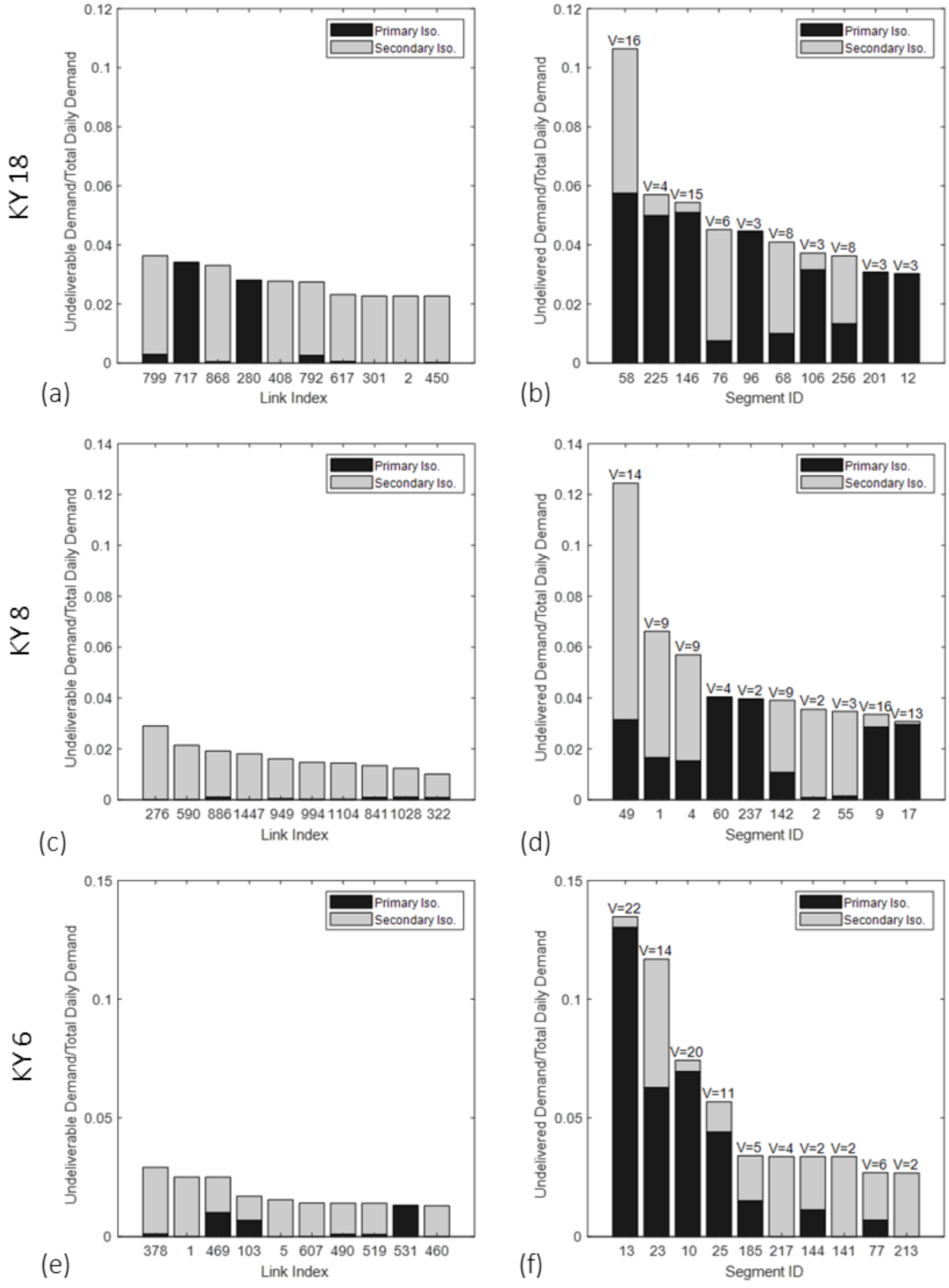

Figure 3-6 Total System Demand Loss Associated with Loss of Pipes (a – c) and Segments (d – f) for systems KY6 (a, d) KY8 (b, e) and KY18 (c, f)

3.8 SUMMARY and CONCLUSIONS

Researchers have proposed varied segment identification methodologies that take advantage of network theory, matrix operations, breadth, and depth first search algorithms (Loganathan and Jun 2007; Kao and Li 2008; Giustolisi and Savic 2010; Alvisi et al. 2011; Gao 2014; Gupta et al. 2014). These methodologies are increasingly efficient, yet they require some manual modifications to the associated network files before they can be applied. The segment identification procedure presented in this chapter seeks to take advantage of the EPANET programmer’s toolkit and use of a preexisting network file. Although the link structure of the input file used for the isolation valves increases the number of elements, the execution time required for the procedure is still adequate for a straightforward segment-based assessment (Figure 3-4). Finally, the development of the methodology within a MATLAB toolkit for use with open source EPANET should allow its direct application by the larger water distribution research community.

This chapter has described an algorithm for identifying both primary and secondary isolation segments along with the associated valves needed to isolate the primary segment. The results of the algorithm may be useful by water utilities to potentially screen for possible reliability issues (e.g. primary segments which require a large number of isolation valves to close or segments with a large number of associated secondary isolations) or be used in more advanced types of analyses (e.g. demand shortage analyses, segment and valve prioritization, valve criticality analyses, optimal placement of valves or other segment strengthening measures, optimal tank placement, cascading valve failure analyses, etc.). The chapter illustrated one possible use in a simple demand reliability analysis, which underscored the importance of using segments in the analysis. More advanced analyses are possible which consider a wider range of impact metrics such as pressure dependent demands, fire flow demands, extended period simulations, and water quality analyses

In the end, segment-based assessment analysis should provide design engineers with additional insights into the potential impacts of possible pipe breaks or pipe maintenance. Thus, the proposed segment-identification method could be used as the first step to analyze emergency response planning and network reliability appraisals since it explicitly considers the role of isolation valves in determining isolated valve segments.

3.9 REFERENCES

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CHAPTER 4. SEGMENT-BASED ASSESSMENT OF THE CONSEQUENCES OF FAILURE ON WATER DISTRIBUTION SYSTEMS

This chapter includes an article that has been accepted for publication (Hernandez Hernandez, E. and Ormsbee L., 2020). "SEGMENT-BASED ASSESSMENT of the CONSEQUENCES of FAILURE on WATER DISTRIBUTION SYSTEMS"

4.1 ABSTRACT

Pipe breakages, leakages, and other failure events in water distribution systems (WDS) are a permanent concern of local utilities. This concern is amplified by the aging of the water infrastructure, increasingly complex systems, and the potential threat of natural or man-made disruptions. Therefore, initiatives to mitigate and plan for future failure conditions have been progressively prioritized. A central component of this effort is to examine the scale of the consequences from a failure event.

Typically, failure simulations have considered pipe breakages by taking out of service one link at the time. However, in most networks the impact of a pipe breakage is not constrained to a single element; but the true extent of the consequences is defined by the number, location, and reliability of valves that are required to isolate the broken pipe from the rest of the system.

This chapter proposes a simple methodology that uses *segments*, the smallest set of pipes that can be isolated by the available valves, to evaluate the performance of the distribution network under a failure condition. The assessment method uses a series of segment failures instead of single link isolations and identifies the location of critical segments using performance metrics based on loss of connectivity, reduction in demand satisfaction, and the ability to fulfill fire suppression requirements. Although significant advancements have been made in the modeling of water networks using segment-based approaches, the shortfalls that the proposed metrics seek to quantify have not been evaluated and compared using a real water distribution network.

4.2 INTRODUCTION

A substantial portion of the water infrastructure in the United States was originally installed between 50 and 100 years ago (ASCE 2017). The consequences of this condition can be observed in the most recent ASCE infrastructure report (2017), where it is estimated that approximately 240,000 water main breaks occur each year in the United States. Although operational strategies or structural changes have been proposed to reduce pipe breaks and related repairs, the likelihood of systems being able to completely avoid such needed repairs even with a renewed infrastructure is remote. Moreover, pipe repairs and replacements can be costly and utilities in charge must often address these with limited resources while striving to maintain adequate levels of service.

Once a break occurs or a repair becomes necessary, large-scale effects are typically experienced across the system (Barker et al. 2013). Thus, quantifying the consequences of failure events is often regarded as a sensible practice since it allows for contingency plans and mitigation strategies to be developed. Although leakages are habitually more frequent in water distribution systems, larger pipe breakages or component outages are often more emphasized since they can have more prevalent impacts stemming from a single occurrence.

In the past, most research methods have characterized each pipe break, regardless of the cause, as the loss of a single element (Bao and Mays 1990; Ormsbee and Kessler 1990; Park and Liebman 1993; Gupta and Bhave 1994; Diao et al. 2016; Ayala-Cabrera et al. 2019). This implicitly assumes that all pipes in the network have isolation valves at both ends that can be readily located and operated.

Currently, there are not any universally governing regulations on isolation valve placement. Isolation valves are typically placed near pipe intersections with the usual rule of thumb being to install at least N-1 valves at each intersection (where N = the number of intersecting legs of pipes). Designers may also decide on a more conservative approach by placing N valves at an intersection, one valve for each leg at the junction, to minimize the compromised area (Walski et al. 2006), however this strategy is hardly used due to economic considerations. Placing valves along long pipes is not limited to junctions. Frequently cited criteria for isolation value placement include the AWWA’s Introduction to Water Distribution (1986) and the Ten State Standards (GLUMRB 2012), which suggest locating valves at no more than 150 m (500 ft) intervals in commercial areas and at no more than 240 m (800 ft) in the rest of the system; while in areas with widely scattered customers valve placement intervals should not exceed 1600 m (1 mile).

Using a segment-based approach the proposed methodology considers that several of the neighboring pipes may also be taken out of service depending on how the valve layout allows for the isolation of the failed component (Figure 4-1). The term segment, first introduced in this context by Walski (1993), is used to describe the smallest segment of the distribution system (as characterized by a set of pipes or sections of pipes) that can be isolated by the closest available isolation valves. The concept of a segment reflects more accurately the number and spatial distribution of the elements taken out service when a component failure needs to be addressed than the use of a single link (Walski 2020).

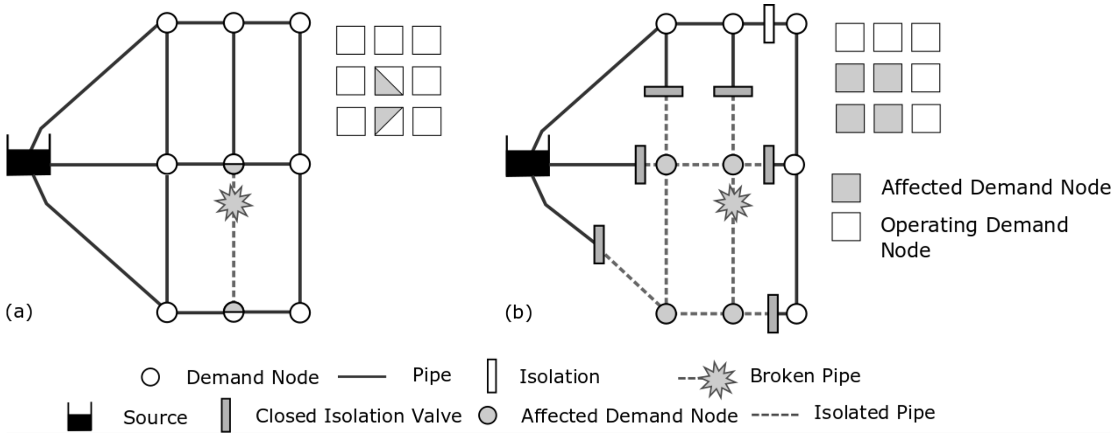

Figure 4-1 Single link failure compared to (b) segment failure caused by the same pipe breakage

A segment failure can be produced by a variety of conditions: pipe breakage, leakages, or maintenance operations. Although these events typically originate from a single component, a larger area enclosed by the surrounding isolation valves is taken out of service to isolate the single element from the rest of the system. Defining the failure condition as the failure of a segment as opposed to an individual pipe has some useful implications: (1) taking a segment out of service incorporates the multitude of causes that might require shutting down a section of the network (e.g., breakage of any of the lines within that section) thereby reducing the total decision variable state space; (2) it reduces the number of scenarios that are considered, since regardless of the cause, the failure event will require placing the entire segment out of service; (3) and it emulates more closely the situation that would be experienced during a failure in a real system when compared to the hypothetical scenario of a single element out of service.

4.2.1 Previous Research

Incorporating the use of segments (Walski et al. 2006; Jun et al. 2008; Kao and Li 2008; Creaco et al. 2010; Giustolisi and Savic 2010; Creaco et al. 2012; Gupta et al. 2014; Kim et al. 2019; Giustolisi 2020) and similar structures (Giustolisi et al. 2014; Giustolisi and Ridolfi 2014) as part of valve and reliability assessments has steadily increased in recent years, extending to the development of tools to identify potential segments such as the Strategic Valve Management Model (Deb et al. 2006), and to inclusion of valve criticality analysis in commercial software (Bentley Systems 2019). For instance, Kao and li (2007; 2008) used valve enclosed segments in a water distribution network to determine how pipe failures could impact the water supply while also proposing how these assessments could be used as a resource to optimize pipe replacements in a distribution network. On the other hand, Berardi et al. (2014) evaluated the impact of multiple segment shutdowns on the total supplied demand to identify the most disruptive scenario. Similarly, others have analyzed the effects of district metered areas (DMAs) or other network partitions and their influence on the ability of a network to provide service in face of strenuous circumstances (Herrera et al. 2016). A segment or an isolation zone approach, unlike other approaches recognizes the role of valves, and their impact on reliability and system operation.

Valve locations determine the scale of the impact of a failure, with better distributions leading to less shortcomings in service. Accordingly, methods to optimize valve placement and improve valve performance have also appeared in the literature (Reis et al. 1997; Ozger and Mays 2005; Deb et al. 2006; Creaco et al. 2010; Giustolisi and Savic 2010; Gupta et al. 2014; Choi et al. 2018). Naturally, the use of valves as elements to increase system reliability raises concerns regarding the likelihood of valve operability (Deb et al. 2006; Walski et al. 2006; Jun et al. 2008). More recently researchers have begun to evaluate both the criticality of individual valves as well as the consequences of valve failure in addition to link failure (Walski et al. 2006; Jun et al. 2007; Jun et al. 2008; Liu et al. 2017; Shuang et al. 2017).

While the use of segments to analyze the behavior of water distribution networks has been increasingly adopted over the last decade, only a handful of assessment tools have been proposed that address multiple types of impacts. Part of the reason for the lack of more complex assessments is the additional computational requirements typically required by such analyses. While several researchers have tried to avoid this problem by employing surrogate metrics or graph-based assessments (Liu et al. 2017; Nardo et al. 2018; Balekelayi and Tesfamariam 2019; Giustolisi et al. 2019; Sitzenfrei et al. 2019), there remains a need for either 1) the use of more advanced and computationally efficient assessments that take into account additional critical evaluation criteria or 2) a way to validate more simplified metrics using full-blown assessments applied to real world systems. In the present chapter the author explores the use of four different assessment metrics to evaluate the resilience of a real-world system in response to segment failures. The four assessment metrics: one topological and three hydraulic (one under normal average daily demand conditions, one under fire-flow conditions, and one that evaluates the actual hydrants themselves) provide a basis of comparing the computational requirements of each approach as well as evaluating the potential utility or benefit of using more advanced assessments. To date, such an assessment has not been reported in the literature, at least not using a real distribution system and actual valve locations and with additional metrics that evaluates the impact of segment failures under what might be considered the most critical demand scenario: fire suppression conditions.

In this dissertation, a method is proposed that uses a segment-based approach to explicitly consider valve locations and their role during a partial system shutdown for multiple assessment metrics. In order to make the proposed approach more readily available to both the water distribution research community and actual water utilities the methodology has been constructed using the MATLAB EPANET Toolkit (Eliades et al. 2016) which makes use of the open source EPANET (Rossman 2000) hydraulic engine.

4.3 SEGMENT-BASED ASSESSMENT MODEL

The segments defined by the existing layout of a network are typically identified using an algorithm based on a breadth-first search (Bondy and Murty 2007) and the use of connectivity or adjacency matrices; with a number of segment identification algorithms proposed by various researchers (Loganathan and Jun 2007; Giustolisi and Savic 2010; Alvisi et al. 2011; Gao 2014). In the current study, the author has adapted an approach akin to that of Loganathan and Jun (2007) but explicitly modified to take full advantage of the network file structure of EPANET (Rossman, 2000). The full details of the algorithm are reported in Chapter 3. To optimize the computational efficiency of the algorithm while still taking into consideration the exact spatial placement of the valves, the algorithm takes advantage of the representation of valves in EPANET as links. Consequently, the pipes belonging to a segment may be represented as fractional elements (i.e. a section of pipe segmented by one or more isolation valves - the latter of which can occur with long transmission mains). This feature eliminates the necessity of assuming that all valves must be placed near existing junction nodes (which as we have observed in working with real systems does not always occur). Once executed, the algorithm defines each segment as well as any additional secondary or unintended isolations (i.e. sections that are disconnected from the source as a consequence of a primary segment failure). Once the segments have been identified the segments are failed sequentially and their impact is assessed based on the unfulfilled demands, deficiencies in pressure, and/or the ability to satisfy fire protection requirements.

4.3.1 Performance Metrics

The proposed algorithm assesses the impacts of a segment closure by employing four different performance metrics: (1) a *topological metric* that quantifies the loss of total system demand due to the direct or secondary isolation of sections from any available source (i.e., reservoirs, tanks) , (2) a *pressure dependent normal demand metric* that quantifies the loss of total system demand due to deficient pressures resulting from increased headloss through the system stemming from the isolation of a segment, (3) a *pressure dependent fire demand metric* that quantifies the loss total system demand, again resulting from increased headloss that results from isolation of an segment of pipes, a maximum day demand, and a single fire demand and/or the loss of adequate head from tank depletions, and (4) *a pressure dependent hydrant demand metric* that quantifies the average loss of available fire flow protection from a single hydrant resulting from the isolation of an individual segment of pipes.

4.3.1.1 Topological Metric (TM)

The topological metric quantifies the decrease in the level of service provided once a segment is isolated or shut down by measuring the decrease in the supplied demand. It considers the nodal demands that will not be satisfied as a result of the physical isolation of the failed segment from the rest of the system or the inaccessibility of other segments to any of the available sources (i.e., secondary isolations). This metric treats the demands at each node as a fixed value, that is, the demands are assumed to be not affected by the residual pressures that may result at the node. This measure is an approximation that does not require a hydraulic simulation and reflects the reachability to the remaining segments after the initial closure, in other words it indicates if there are pathways still available between the nodes and a source (Wagner et al. 1988). Historically similar measures of supply shortages have been used in early vulnerability assessments and failure simulations (Kao and li 2007; Creaco et al. 2012; Berardi et al. 2014; Jung et al. 2016). This metric is analogous to the topological metric used by Creaco et al. (2012).

In actual water distribution systems, the demands are distributed along the pipe through several service connections, However, in most water distribution system models the demands along a pipe are typically lumped together and then equally apportioned to each of the adjacent nodes (i.e. 50% of the total distributed to each node). In determining the loss of demands using a segment approach, the current algorithm apportions the demands based on the fractional location of the valve along the isolated pipe.

Once a segment is taken out of service, the customers located within that section (as conceptualized by lumped demands at each junction node) will be completely cut off from service if there are no secondary sources present within the enclosed area.

The demand shortage associated with each segment failure is then used as the topological performance metric for that segment which serves as an indicator of the loss of connectivity in the water distribution network. This metric can be calculated using equation (4-1).

$$\mathrm{TM}_s = \frac{Q_T - Q_{R\_TM(s)}}{Q_T} = \frac{Q_{TM(s,1)} + Q_{TM(s,2)}}{Q_T} \tag{4-1}$$

$$Q_T = \sum_{\mathrm{i}=1}^{n} q_i \tag{4-2}$$

$$Q_{R\_TM(s)} = \sum_{\mathrm{j}=1}^{m(s)} q_j \tag{4-3}$$

Where TM$_s$ = the topological metric for segment s, s is the segment number, n is the total number of demand nodes in the network, q_i is the demand at node i, Q_T is the total demand allocated to the network, $Q_{R\_TM(s)}$ is the demand that can be fulfilled when the segment s has failed, and $m(s)$ are the nodes which continue to operate. Further, $Q_{TM(s,1)}$ is the shortage experienced in the network as the direct result of the shut-off for segment s and $Q_{TM(s,2)}$ is the shortage due to unintended isolations. This performance metric is calculated sequentially for all identified segments.

Although this metric provides an indication of the loss of demand associated with isolating segment s, from primary and secondary isolations, it does not consider how the nodal pressures might be affected across the network. In order to provide this type of assessment a *pressure dependent normal demand metric* is used.

4.3.1.2 Pressure Dependent Normal Demand Metric (PDND)

Similar to the topological metric, the PDND metric includes the impact of nodal demands that cannot be supplied due to primary and secondary segment isolations. However, in evaluating this second metric, a hydraulic simulation of the system is performed for each isolated segment and the pressures associated with the remaining functional nodes are then evaluated.

Historically, hydraulic simulations have been assumed to operate under demand driven conditions, where regardless of the nodal pressure at the junctions the required demand is assumed to delivered. In recent years, several modelers have attempted to represent this variable pressure/discharge phenomenon more explicitly by incorporating variable demand functions directly into the simulation models (Bhave 1981; Goulter and

Coals 1986; Su et al. 1987; Gupta and Bhave 1996; Tucciarelli et al. 1999; Pacchin et al. 2016; Walski et al. 2019). While such functionality may be justifiable when modeling intermittent supply systems were low pressures are experience such as those observed in cities in India (Ingeduld et al. 2008; Klingel 2012), Schück and Lansey (2018) have recently raised questions about the legitimacy of such approaches for more conventional (i.e. continuous water supply) systems like those in the United States. Nonetheless, several authors have extended the application of variable demand modeling to problems involving pipe failures (Kao and li 2007; 2008; Giustolisi et al. 2014; Gupta et al. 2015; Qi et al. 2018). In this case the reduction in the theoretical provided demand can be used to serve as an indicator of the "level of loss of service" since while the associated users may still have access to some water supply, it may take longer to receive the desired volume.

In evaluating the PDND metric, the nodal pressures that result from a steady state analysis of the system after a segment failure is compared to the minimum pressure expected during normal conditions (i.e. 241 kPa or 35 psi) and a desired pressure which will correspond to the observed value before the segment failure (Mays 2000; Ghorbanian et al. 2016). These pressures will be used to estimate the expected actual deliverable flow using a supply function which relates outflow and nodal pressure. In order to approximate pressure dependent demands using a single static hydraulic simulation, the outflow delivered at the nodes will be determined using the following equations as first suggested by Wagner et al. (1988)

$$q_j^a = 0 \text{ , if } H_j^a \leq H_j^{min} \tag{4-4}$$

$$q_j^a = q_j^{des} \sqrt{\frac{\left(H_j^a - H_j^{min}\right)}{\left(H_j^{des} - H_j^{min}\right)}} \text{ , if } H_j^{min} < H_j^a < H_j^{des} \tag{4-5}$$

$$q_j^a = q_j^{des} \text{ , if } H_j^a \geq H_j^{des} \tag{4-6}$$

where q_j^a is the assumed outflow delivered at node j, q_j^{des} is the desired demand at node j, H_j^a is the pressure head experienced at node j, H_j^{min} is the minimum pressure head requirement at node j and H_j^{des} is the pressure head for node j corresponding to the desired demand. Given that the hydraulic simulations are based on a single solution using a of a demand driven steady state hydraulic solver, this may be technically considered a quasi-pressure dependent approach (Zhuang et al. 2013).

Prior to generating the PDND impact metric for each segment, a static hydraulic simulation of the original network is performed and the resulting pressures at each node are recorded and stored as H_j^{des}. Next a new network configuration is created for each segment s identified in the network, where the original network is simulated with the closure of the primary segment s and any subsequent unintended secondary isolations. A series of static hydraulic simulations are then performed for each configuration and the assumed demand delivered to each non-isolated junction node is determined using equations (4-4)-(4-6). By virtue of using a quasi-pressure dependent approach it is recognized that the resulting assumed demands may not necessarily be exactly equal to those that would be observed in the system but instead are being used as approximations for the purposes of computing a relative performance index.

Once the assumed demands for the junction nodes in each configuration are determined, an estimate of the total system demand that can be provided for each configuration s can now be calculated using:

$$Q_{(s)} = \sum_{\mathrm{j}=1}^{m(s)} q_j^a \tag{4-7}$$

Where $m(s)$ is the total number of remaining active junction nodes j in the network associated with configuration s. The PDND for each configuration s can now be determined using

$$\mathrm{PDND}_s = \frac{(Q_T - Q_{PDND\,(s)})}{Q_T} \tag{4-8}$$

4.3.1.3 Pressure Dependent Fire Suppression Metrics (PDHD and PDFD)

From the author perspective, fire suppression requirements represent a more critical loading assessment than those associated with normal demands and one in which a pressure variable demand application makes more sense. As a result, the author proposes to use fire flow demands to estimate two additional metrics of system performance: A Pressure Dependent Hydrant Demand metric (PDHD), and a Pressure Dependent Fire Demand metric (PDFD).

4.3.1.3.1 Pressure Dependent Hydrant Demand Metric (PDHD)

Historically, the pipe sizes for smaller municipal water systems are dictated by fire suppression requirements instead of typical potable water demands (National Research Council 2006; AWWA 2008). Unlike static potable demands, most fire demands also have an associated duration to assess both the adequacy of the residual fire flow pressures as well as the available volume in storage for fire protection. In most cases, systems should be designed to maintain a minimum residual fire flow pressure of 138 kPa (20 psi), while the duration of the fire flow will be dependent upon the magnitude of the fire demand as derived from the International Fire Code (2014). Using these criteria, the fire suppression capabilities of the system associated with each isolated segment were evaluated using a single hydrant demand of 63 liter/sec (1000 gpm) for a 2-hour fire duration.

Unlike the normal demand scenarios, additional modifications are made to the system to simulate each fire suppression scenario. First, for each of the s segment configurations, $m(s)$ nodal demands are set to the maximum day demand for the system and any remaining operational tanks are set to half-full, following typical recommendations for fire flow simulations (AWWA 2011). Second, fire hydrants are modeled in the network by placing an additional junction node (to represent the hydrant) along with an additional six-inch diameter spur which is then connected to the closest junction node in the pipe which the hydrant is actually located. This hydrant junction node will be used to add the fire flow demand and to check the residual pressure (using the actual elevation of the hydrant).

During each shutdown s, the remaining hydrants which have not been rendered inoperable by primary or secondary isolations are first identified. Next, each hydrant is simulated independently (one at a time) by placing a fire-flow requirement (i.e., 63 liter/sec or 1000 gpm) at the associated hydrant junction node and then performing a 2-hour extended period simulation (EPS). The pressure head at each hydrant location for the initial ($H_k^{t=0}$) and final time period ($H_k^{t=t_f}$) are recorded in addition to the pressure at end of the EPS for all the other regular junction nodes ($H_j^{a,t=t_f}$). After each simulation, the fire-flow supplied at the hydrant associated with that simulation is then determined using equations (4-4)-(4-6), with a minimum pressure requirement of 138 kPa (20 psi) or 14 meters of head ($H_{min,h}$).

The computational process can be summarized as follows: 1) hydrants are first added to the network, 2) the algorithm eliminates each segment (and any associated secondary isolations) one at a time, 3) the algorithm then performs individual fire-flow simulations for each hydrant that has not been isolated for that segment, 4) the pressure dependent volume of fire flows from each hydrant k in each segment s, is then recorded as ($V_{ff\ (s,k)}$).

Once the individual fire-flow demands supplied at each hydrant during the closure of a segment s are determined, the aggregated total volume $V_{ff(s)}$ for each segment s can now be calculated using:

$$V_{ff(s)} = \sum_{k=1}^{h(s)} V_{ff\ (s,k)} \tag{4-9}$$

Where $h(s)$ is the total number of hydrants that could be individually tested for each configuration s. This volume is compared to the desired aggregated fire-flow volume requirement for each segment shutdown $V_{T_PDHD\ (s)}$which is obtained using:

$$V_{T\_PDHD\ (s)} = \sum_{k=1}^{h(s)} q_k^{ff} \times t_f \tag{4-10}$$

Where q_k^{ff} is the fire flowrate requirement for hydrant k and t_f is the final simulation time (e.g. 2 hours). The fraction of the total volume of required fire flows that fails to be supplied when segment s, and any secondary isolations, are removed (i.e. PDHD $_s$) is then determined using:

$$\text{PDHD}_s = \frac{(V_{T\_PDHD\ (s)} - V_{ff\ (s,k)}\ )}{V_{T\_PDHD\ (s)}} \tag{4-11}$$

4.3.1.3.2 Pressure Dependent Fire Demand Metric (PDFD)

When the fire flows at each hydrant are being simulated, the algorithm also evaluates the flows delivered to all the available junction demands. These flows are then used to evaluate to determine a PDFD metric associated with each s as follows:

$$\text{PDFD}_{s} = \frac{(Q_{T\_PDFD} - \min Q_{PDFD\,(s,k)})}{Q_{T\_PDFD}} \tag{4-12}$$

where:

$$Q_{T\_PDFD} = \sum_{\mathrm{j}=1}^{n} q_j^{max} \tag{4-13}$$

$$Q_{PDFD\,(s,k)} = \sum_{\mathrm{j}=1}^{m(s)} q_{j,k}^{a} \tag{4-14}$$

and where n is the total number of demand junction nodes in the system, q_j^{max} is the maximum day demand for junction j, $q_{j,k}^{a}$ is the assumed pressure dependent demand being met at junction j while hydrant k is being flowed, $m(s)$ is the total number of remaining available junction nodes and $h(s)$ is the total number or remaining available hydrants in the network following the shutdown of segment s (and any associated secondary isolations). In this case, $q_{j,k}^{a}$ is determined using Eqs. (4-4)-(4-6), but now with a minimum pressure head $H_j^{min}$of 138 kPa (20 psi) and an H_j^{a} based the nodal head at the end of the 2 hour fire-flow period. Since there are multiple separate fire hydrant scenarios evaluated for every single segment shutdown, the most detrimental (minimum) result for a given segment s will be used when evaluating the expression min $Q_{PDFD\,(s,k)}$.

4.4 APPLICATION of ASSESSMENT

In order to test the efficacy of the proposed methodology, it was applied to a small water distribution system in the state of Kentucky (see Figure 4-2). The base model used is KY6 (Hernandez et al. 2016) which has been updated to include the locations of the existing isolation valves and hydrants as collected by a recent survey of the area. The system contains 811 pipes, 1401 junction nodes, 235 hydrants, 346 isolations valves, and

1156 pipe elements. A pipe element is a fractional section of pipe that is created when an isolation valve attached to a pipe is closed. Additional details about the system can be obtained from the University of Kentucky Water Distribution Systems Research Database (https://uknowledge.uky.edu/wdsrd/).

Application of the segment identification methodology of Hernandez and Ormsbee (2020) to an EPANET (Rossman 2000) data file of the system resulted in 256 segments. The location of some of the more critical segments are highlighted in Figure 4-2. Summary statistics for most critical segments as identified using the performance metrics are provided in Table 4-2 through Table 4-4

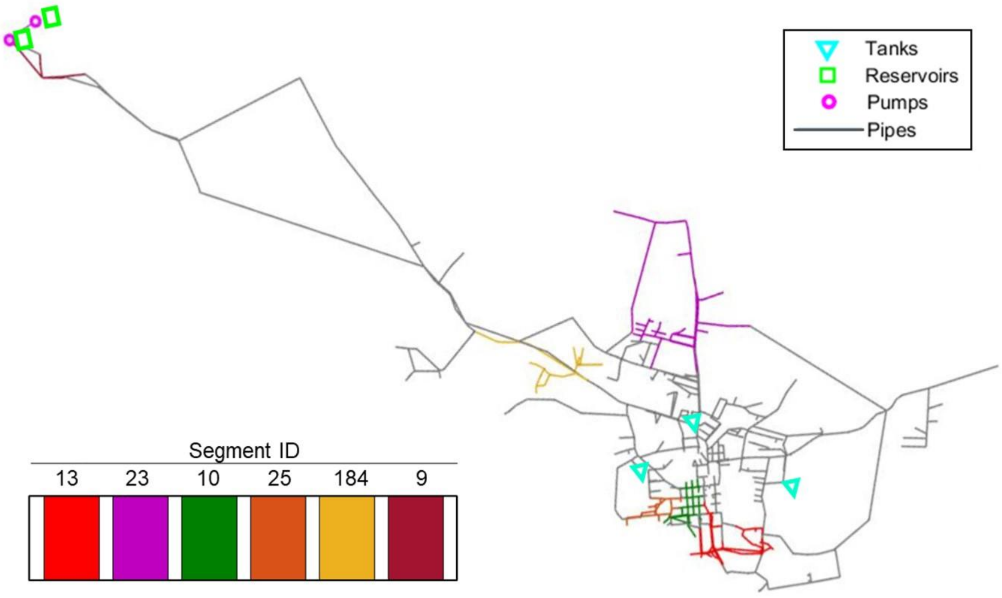

Figure 4-2 KY6 with highlighted critical segments

4.5 RESULTS and DISCUSSION

Statistics for the ten segments whose closure caused the greatest demand impacts are provided in Figure 4-3 (a)-(d). The horizontal axes represent the ID of each the worst ten segments (ranked in order of most impact) while the vertical axes represent the percent of the total demand (or average fire flow demand for PDHD) that is not satisfied when that segment is removed. The V = # atop each bar represents the number of valves required to isolate that segment, while H = # represents the number of hydrants that fail (i.e. those that are not able to meet the minimum pressure requirement) when that segment is removed.

The application of four different assessment metrics in the analysis of an actual water distribution system allows for the exploration of several basic research questions, which are summarized below.

Table 4-1 Performance metrics summary for KY6

	TM	**PDND**	**PDFD**	**PDHD**
Avg	0.62% (All)	0.73% (All)	8.86% (All)	24.96% (All)
Max	13.38% (s=13)	13.39% (s=13)	22.89% (s=13)	28.2% (s=131)
Min	0%(s=1)	0%(s=3)	6.93%(s=110)	21.90% (s=186)
StD	1.41%(All)	2.49%(All)	2.49% (All)	0.84% (All)

1) How significant are secondary isolations?

An examination of Figure 4-3 (a) reveals that while segments 13, 10, and 25 are dominated by losses associated with primary isolations (i.e. indicated in the darker shade in Figure 4-3), the rest are heavily influenced or dominated by secondary isolations. This is also reflected by the statistics in Table 4-2. In fact, the lost demands associated with segments 217, 216 and 140 appear to be nearly all attributable to secondary losses (i.e. indicated in the lighter shading in the figure). For example, closure of segment 216, only results in a small primary isolation of 52 m. by itself (and only two demand nodes), but its removal disconnects a series of additional secondary segments (which include 27 demand nodes) from the available sources. Such results underscore the importance of considering such losses in any resilience analysis.

2) Does the use of a more complex metric (e.g. PDFD vs PDND vs TM) lead to a different ranking of the priority segments?

In comparing the results from Figure 4-3 (a) to (b), it can be seen that the PDND metric (which requires a complete hydraulic analysis for each segment) provides very little change in the order of impact of the associated segments. The three exceptions (i.e. segments 9, 194, and 207) are all included because of the additional pressure dependent loss associated with each segment (as seen by the additional lighter shading in each histogram) which has the net effect of simply shifting the previously ranked segments in Figure 4-3 (a) (i.e. 184, 217, 216) to the right. In contrast, while the PDFD metric yields two of the top ten segments from each of the previous metrics (including the top segment from both – i.e. 13), this metric identifies seven additional segments which are different. Of additional interest is the fact that most of the system loss associated with these segments is not due to associated primary or secondary segment isolated demands, but nearly in all cases due to pressure dependent reductions in the rest of the system due to the imposition of a fire demand. In addition, the total system losses identified by this metric are significantly higher than those identified by the TM or PDND metrics. These observations are consistent with summary statistics for all three metrics as shown in Table 4-1, where the first number in each column represent the percent of the nodal demands that are not meet for that statistic (avg or max) and performance metric, and the second number in parentheses represent the segment associated with that statistic.

Table 4-2 Statistics of the Top Ten Critical Segments (TM metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [m]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Sec. Length	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
13	22	111	6730	110	22	13	737	20	130	225
23	14	55	6481	55	14	54	6259	71	126	205
10	20	61	3536	61	20	8	672	16	77	232
25	11	36	2143	37	11	11	628	16	53	232
184	5	27	3061	28	5	14	1710	18	46	222
217	4	5	4264	6	4	23	3816	29	35	228
216	2	1	52	2	2	22	3764	27	29	230
143	2	4	1398	5	2	15	2140	18	23	230
140	2	3	226	4	2	19	3538	23	27	230
76	6	14	806	15	6	14	845	17	32	233

These results would seem to suggest that while the PDND metric does not seem to add that much additional information versus the TM metric (and thus may be unnecessary), the PDFD metric does seem to be valuable and should be considered when evaluating system resilience. Note: While the increase in the baseline demand for the PDFD fire simulation (i.e. maximum day vs normal day) contributes in part to some of the additional losses, our analyses revealed that it is the actual additional fire demands that produce most of the strain (i.e. > 80%).

It is also important to note that while the PDND metric is based on a steady state simulation, the PDFD is based on a EPS simulation, and thus takes into consideration both a loss of pressures due to increased headloss (from a loss of available flow paths), but also a loss of pressures due to a decrease in the tank water levels. For example, when segment 9 is removed from service, one of the two reservoirs is disconnected from the system, resulting in less water being pumped resulting in a faster depletion of tanks levels. Likewise, if one or more segments contain a tank, then their isolation could not only remove that pressure source from the system, but also result in a quicker depletion of the water levels in the remaining tanks. These observations provide additional motivations for using the PDFD metric.

Table 4-3 Statistics for Additional Critical Segments (PDND metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [m]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
9	4	9	2054	10	0	0	0	0	10	235
194	5	21	6246	22	2	1	258	2	24	230
207	4	20	7878	21	0	0	0	0	21	231

Table 4-4 Statistics for Additional Critical Segments (PDFD metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [m]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
59	4	8	631.6	9	1	1	138	2	11	233
2	2	3	501.6	4	1	1	17	2	6	234
60	2	1	1.2	2	0	0	0	0	2	235
61	2	1	0.6	2	0	0	0	0	2	235
131	5	11	1314.2	12	0	0	0	0	12	232
188	3	3	821.4	4	4	9	1197	13	17	229
183	2	1	0.7	2	0	0	0	0	2	235

3) Does the PDHD metric provide any additional insights to system performance?

In order to provide a direct comparison between the PDFD and PDHD metrics, the order of the segments associated in Figure 4-3 (c) and Figure 4-3 (d) were kept the same. It should be noted that the percent flow reductions listed in Figure 4-3 (d) reflect the average loss of the fire-flow delivered at a single hydrant and not the percentage of loss of the total system demand (as reflected by Figure 4-3 (c)). Of particular interest is that fact that the hydrant flow reductions appear to be fairly consistent (i.e. 23 to 27%) regardless of what segment is eliminated. Perhaps more consequential is the number of hydrants that fail (i.e. indicated by the number above the associated histogram bar). As seen in Figure

4-3(d), this ranges from 48 to 65, which is highly significant, and indicates that loss of any segment could have catastrophic impact on the fire suppression capabilities of the system.

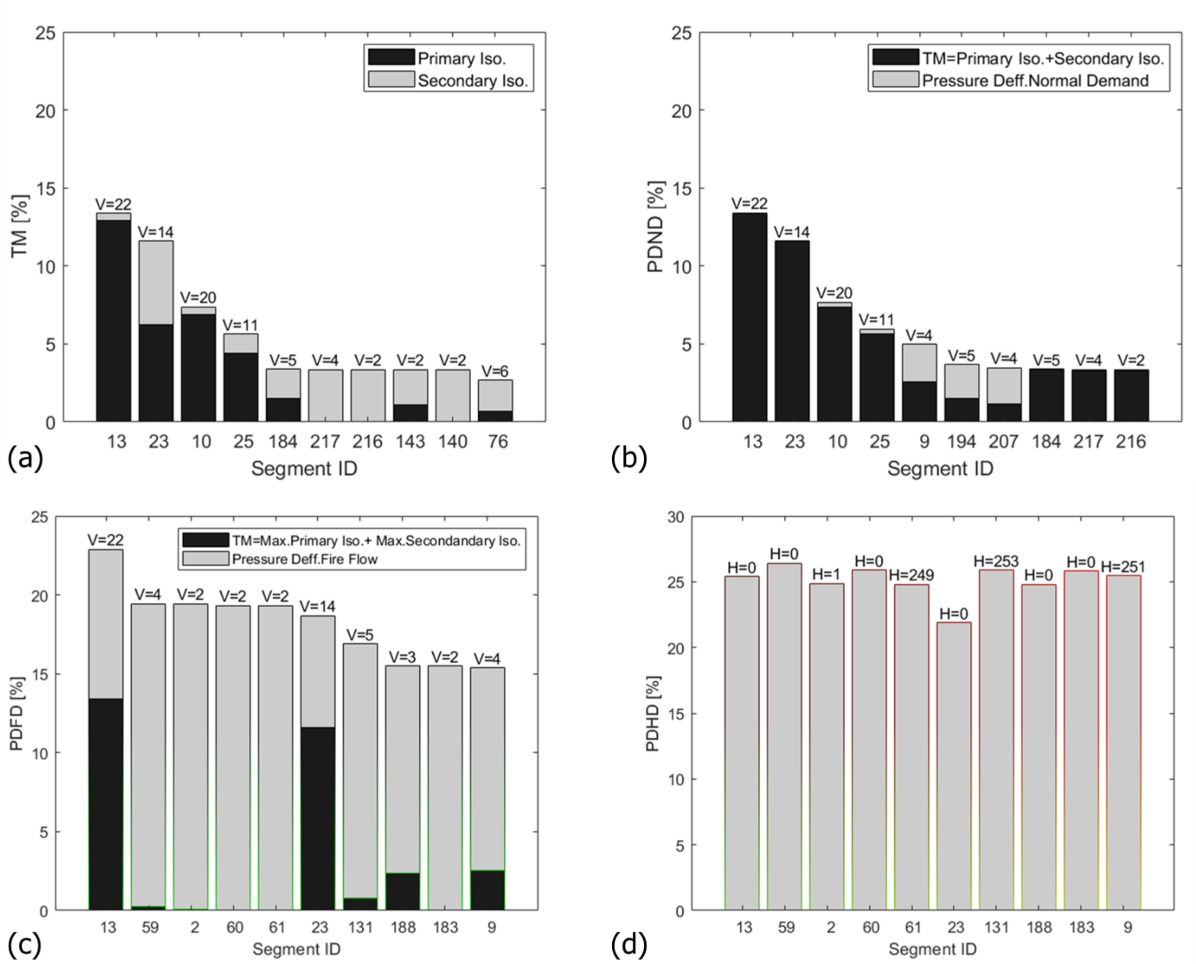

Figure 4-3 Ten most critical segments for (a) Topological Metric (TM), (b) Pressure Dependent Normal Demand (PDND) metric, (c) Pressure Dependent Fire Demand metric (PDFD) and (d) Pressure Dependent Hydrant Demand (PDHD) metric

4) Can simple geometric statistics (e.g. number of isolation valves or the length of the segments) be used as a surrogate for more complex metrics?

It is significant to note that segment 13 (which was identified as the most critical segment using the first three metrics) also has the greatest number of pipe elements, the most number of valves, and the most number of isolated nodes (see Table 4-2). Is it possible that one or more of these metrics might be useful in identifying the critical segments without the need to conduct extensive steady state (i.e. PDND) or EPS (i.e. PDFD) simulations? While a cursory examination of the rest of the segments in Table 4-2 might suggest such a pattern, at least for the first few segments, it becomes clear, that such a pattern is not universal (e.g. segments 23 and 140 for the number of valves, segments 140 and 76 for the number of isolated nodes, segment 76 for the number of pipe elements, etc.). Given the fact that the computation of these statistics takes the same amount of computational time as the TM metric, there seems to be little advantage of such an approach, even if they did provide consistent surrogates.

The real benefit of such surrogates would be if they could be used in lieu of the more computationally intensive metrics (i.e. PDND, or PDFD), and here unfortunately, any such patterns readily break down. Referring to Figure 4-3 and Table 4-3 and Table 4-4, one can readily see that most of the additional segments associated with the PDND or the PDFD metrics fail to follow any such patterns. This should not really be unexpected since both metrics rely on hydraulics simulations, while the TM metric (which shows the greatest correlations) depends solely on topological elements (e.g. the number of valves required, the number of isolated junction nodes, etc.)

4.6 ASSUMPTIONS and FUTURE DIRECTIONS

This chapter introduces a segment-based methodology that uses four different metrics to evaluate a network's performance when facing a condition that requires a partial shutdown. Using segments as the units for the evaluation reduces the number of scenarios considered and departs from the single link failure model. While this chapter has examined the use of multiple metrics in evaluating system performance, additional research questions remain.

An essential assumption of the proposed assessment methodology is that the isolation valves included in the model can be located and operated in response to a pipe or component failure. In practice, valves that cannot be closed would modify the segment distribution, easily increasing the size of the compromised area and the associated impacts. The likelihood of a failure to find or operate a valve has not been introduced into this assessment due to the lack of more specific information, thus the potential for segment expansion has not been explored.

As presented, the assessment has only considered the consequences of failure and not the probability of failure of a segment or the pipes associated with the segment.

A natural expansion of the current work would be to consider the likelihood of failure of the pipes, segments and isolation valves themselves.

Similarly, the current assessment focuses on short-term consequences of a segment shutdown. Presently there is no consideration of the repair time, yet the assessment assumes that the shutdown would be experienced for at least two hours under the fire suppression scenario. A more meaningful review incorporating resiliency could be provided if the typical repair times for the analyzed systems were explicitly known. If a critical segment failure can be addressed in a short time frame then the consequences of the failure itself are greatly diminished. However, as the repair time increases the associated impact could also increase. These consequences have not been considered in the present analysis. Furthermore, there is an assumption that the impacts of all system shortages are the same, that is, no explicit consideration has been made for the types of facilities that would experience such shortages (e.g. homes, schools, businesses, hospitals, etc.). Obviously, an explicit consideration of such factors could greatly impact the level criticality of such segments. While such a consideration could be incorporated by appropriate segment weighting factors, such an analysis has not been done in the current study.

Finally, it may be possible to use segment analysis to help guide the location and design of system components (e.g. pipes and valves) to optimize the resiliency or reliability of the system. Several researchers have already suggested optimization procedures (Ozger and Mays 2005; Giustolisi and Savic 2010; Alvisi et al. 2011) that could be adapted to different assessment frameworks. Moving to pair this assessment with an optimization protocol could provide an improved valve layout for small water distribution systems and support capital improvement planning.

4.7 SUMMARY and CONCLUSIONS

Four different metrics have been developed for use in the analysis of the reliability of an actual water distribution system by considering existing isolation valves and the associated segments that would be isolated in the event of a pipe failure. For the system examined, the following conclusions can be made:

- It appears that TM metric is sufficient to identify the most critical segments under normal demands without the need for calculating a more computationally intensive PDND metric.
- While it appears that a few of the related segment statistics (e.g. the total number of isolated elements, etc.) may be used as surrogates in identifying the segments that require most immediate intervention, at least for the TM metric and for the single analyzed system, this pattern does not consistently hold for the PDND and PDHD metrics. Further, since the TM metric requires no additional computational burden, the use of such surrogates, even if the provided consistent and reliable, would not seem warranted.
- The PDFD metric gives sufficiently different results from either the TM or PDND metric to suggest that it may have some additional utility in the reliability assessment of a network. While the PDHD metric provides some additional information regarding the expected system performance of the actual hydrants under fire conditions, it does not seem to provide much utility in helping to identify or differentiate critical segments. However, since the associated results are computed alongside of the more robust PDFD metric with minimal additional computational burden, it would make sense to compute the PDHD at the same time.
- While the current methodology does not provide any such explicit guidance with regard to optimal valve and pipe placement, the use of the proposed metrics can help the utility to identify potential segments that could be problematic and thus guide additional focus. As an example, if a segment is identified that requires the closure of 22 valves, then it would seem prudent that the utility might want to examine that segment for additional division or to confirm that no smaller segments actually exist. While this seems like an unusual number of required isolations valves, this number was obtained directly from the utility. More likely it is possible that there may be other valves (either lost, buried, or broken) that could provide smaller segments. However, this situation is typical with a lot of smaller utilities and thus the data provided simply reflects the actual operational

constraints under which the utility is currently operating. At a minimum, the proposed algorithm provides a tool to highlight such deficiencies.

- It is recognized that each of these conclusions is dependent upon the results of one single distribution system. While the fact that the system is an actual distribution system provides some credibility to the results and the associated conclusions, additional analyses with other real systems will be needed in order to verify these observations. The author is currently contributing to assemble such a database for such a purpose as well as for use by the larger research community. Once assembled it will be posted on the University of Kentucky Water Distribution Research Database for wider disbursement.

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CHAPTER 5. VALVE PLACEMENT OPTIMIZATION PROCEDURE

5.1 ABSTRACT

In water distribution systems the location of isolation valves defines the boundaries of the section of the network that will be taken out of service when an unexpected outage occurs or when planned maintenance is required. This means that the existing placement of isolation valves in a system will ultimately define the shortage in supply experienced by the customers and contributes to the reliability level of the system. In this paper the author proposes an iterative framework to improve the current valve distribution in a distribution network while taking into consideration existing valve locations. The method takes advantage of graph theory concepts to define an improved valve placement scheme that provides gradual upgrades using a minimum amount of new isolation valves at each step. Two objective functions are tested (1) reduce the experienced service shortfall to a target limit and (2) decrease the number of isolation valves required to isolate individual system subsections (i.e. segments). The proposed framework decreases supply cut-off and aims to provide a continuing improvement strategy that could be applied by utilities with limited resources. The method is applied to the real valve layout of a water distribution network to demonstrate the feasibility and utility of the procedure.

5.2 INTRODUCTION

In water distribution systems there is no universally agreed upon definition of reliability. Researchers have recognized that the question of reliability is confounded by the complex nature of water networks, i.e. there is a number of interconnected elements (i.e. sources, pipes, pump stations, valves, regulators, tanks) that continuously interact with each other changing the various parameters that have been used in the past for both the definition and quantification of reliability (Mays 2000; Ostfeld et al. 2002).Because of this, there are a variety of analytical and simulation methods to estimate it. Often, the analytical metrics have relied on a heuristic approach, such as providing alternative paths to maintain topologic redundancy (Ormsbee and Kessler 1990).

or ensuring that each demand node is connected to at least one source (Goulter 1988; Wagner et al. 1988). These approaches generally depend on the physical characteristics of the network or its configuration as implicit indicators of reliability. More recently these approaches have explored a range of surrogate measures that rely on graph theory concepts. These graph-based approaches take advantage of the fact that the elements of a water distribution system can be simply represented as links (e.g. Pipes) and nodes (e.g. Junction nodes, sources), thus the network could be defined as an undirected graph $G = (V, E)$, where the V elements are the nodes (or vertices) of the graph G and the links (or edges) are the elements of E. This definition of the distribution network as a graph has allowed researchers to explore several different metrics of reliability, including centrality measures (Giustolisi 2019), entropy (Tanyimboh and Templeman 2000), betweenness (Agathokleous et al. 2017), eigenvector centrality (di Nardo et al 2018), among others (Giudicianni et al. 2018; Nardo et al. 2018).

In contrast to analytic methods, simulation methods usually aim to measure the level of service with the aid of network solvers and the introduction of stochastic simulation methods. Thus, this type of approach would encompass the simulation of the failure event, including a hydraulic analysis of the failure condition (Wagner et al. 1988). These methods have also introduced the use of pressure dependent simulations, instead of the commonly used demand driven model, to consider the effect of pressure on the flow delivered at the point of consumption (Kao and li 2007; Creaco et al. 2010; Gupta et al. 2014). Simulation methods allow for more system specific conditions, but they can require significantly increased computation times when compared to analytical methods. Because of this, some researches have opted for the use of a combination of analytical and simulation approaches for a more complete reliability assessment without requiring extensive computations (Wagner et al. 1988). Regardless of the approach used, in the most general terms reliability could be understood as “any measure of the system’s ability to satisfy the requirements placed on it” (Mays 2000). Moreover, as reliability has continued to become a pressing concern for utilities (Walski 2019), and it has been increasingly incorporated in optimization frameworks. This is particularly true in the United States where water infrastructure has been historically underfunded and continues to steadily approach the end of its useful life (AWWA 2012; ASCE 2017)

Early optimization procedures focused on least-cost design which alone might not guarantee reliability, since many implicit redundancies of the network are typically removed when exclusively pursuing a least-cost solution (Mays 1989). Yet, as computational resources continue to become more accessible, reliability has been increasingly incorporated in the formulation of optimal design problems. These optimization approaches typically combine a reliability assessment method (for use in quantifying the objective function) and an optimization procedure. The former component may consider element failures such as pipes and pumps (Goulter and Coals 1986; Su et al. 1987; Ormsbee and Kessler 1990), or the ability to perform beyond a minimum set of hydraulic requirements (Xu and Goulter 1999; Tolson et al. 2004; Farmani et al. 2005). However, most approaches have assumed that individual pipe breaks can be isolated from the rest of the system by simply removing from service the line that contains the break. This implicitly assumes that each pipe contains an isolation valve at either end and that these valves can be readily located and operated. Still, this is rarely the case in actual distribution systems. As a result, many researchers have now proposed the use of pipe segments vs individual pipe links in the evaluation of network reliability. In this case a segment is defined as the smallest subsection of the network that can be isolated by the closing the closest isolations valves in proximity to the pipe break (Walski 1993). Despite this recognition, very little research has been pursued in this direction (Mala-Jetmarova et al. 2017; 2018). Nonetheless, some related work has been reported by Bouchart and Goulter (1991) that focused on reducing pipe length, and consequently their impact upon failure, by adding new isolation valves along the links; Ozger and Mays (2005) proposed the use of a simulation annealing algorithm to optimize the valve placement in a new network ; Giustolisi et al. (2008) suggested a new algorithm to detect the segment defined in the network by the existing isolation valves and coupled it with a pressure dependent simulation model; while Alvisi et al. (2011) introduced a segment identification method that makes use of an auxiliary matrix to record and vector to record the location of the isolation valves, and then combined it with an adapted genetic algorithm (NGSA II) to redesign the isolation valve layout of a system seeking to minimize the number valves installed and the maximum demand loss; conversely, Gupta et al. (2014) proposed an iterative optimization process to increase the level of reliability of the network by using one of three alternatives in each iteration, (1) an addition of a valve(s) to pipe(s) without a valve; (2) an addition of a parallel pipe to an existing pipe; and (3) an increase in size of newly added pipes ; and Giustolisi (2019) developed a reliability indicator for a valve system using a pressure dependent hydraulic simulation and the probability of segment failure, thereby extending testing of the reliability of the isolation valves themselves. This new index, which considered segmentation and the possible valve malfunctions, was then used as part of the optimization of the valving for a network. The optimal design had as an objective to reduce the hydraulic and topological impact of a segment failure, while minimizing the total number of valves added.

Nonetheless, in the analysis and optimization of water distribution systems, the role of isolation valves has received limited attention when compared to other elements (e.g. pumps, tanks, pipes). However, it is isolation valves that allow a subsection of the network (i.e. segment) to be separated from the rest of the system when repairs or maintenance are necessary. This means that when a distribution system only has a few valves, or they are poorly distributed, large sections of the system will have to be taken out of service when a failure occurs. Historically, the placement of isolation valves has followed general rules of thumb instead of system specific guidelines (Walski 2006). For instance, one of the most encountered rules of thumb is the is to install a minimum of *n-1* valves around a junction to which *n* pipes are connected. Similarly, the *n* valve rule of thumb recommends placing valves around all *n* pipes incident to a junction. This placement will locate valves at both ends of each pipe of the system. Nonetheless, this type of placement will require a large capital investment to install the isolation valves and a continued allocation of funds for valve maintenance (e.g. annual valve exercising, operating valves to full cycle and returning them to the fully open position at least once a year) which is often not feasible. Other guidelines suggest placing valves less than 500 ft in commercial districts and at a maximum of 800 ft in other areas (Deb et al. 2006). In terms of reliability the location of the isolation valves can affect several factors: the extent of the section that will be taken out of service to address an emergency condition or make repairs, and the ability to shut down a section will be dependent on the successful operation of all valves enclosing it. These factors illustrate the challenges of appropriate valving. These include placing valves in a layout that creates segments with manageable losses in service that can be quickly isolated by using a low number of valves. The latter aspect is of importance since there is little information on the reliability of the isolation valves themselves (i.e. the ability to be fully operable when required) and so the higher number of valves required for a closure will increase the likelihood a given section cannot be isolated and that the area taken out of service will spill over the original bounds.

In this paper the author proposes a heuristic approach to increase the level of reliability of the network by improving the existing valve layout of the systems. The method provides a solution that can be applied in gradual steps while aiming to maintain the lowest possible number of valves added. The author starts with a water distribution system that already has valves in place. and then explores where it would be most beneficial to add new valves. This means that each valve location suggested is based on the existing condition, which may allow utilities with limited resources to invest in the rehabilitation of the network under a phased approach. The method is applied using two objectives (1) the reduction of supply shortage as estimated by identifying the resulting isolated topological network and (2) decreasing the maximum number of valves required to isolate an individual segment. While most previous work has focused on increasingly reliability without an explicit consideration of the number of valves required for each segment, the method proposed by the author places more emphasis on reducing the number of valves needed for each closure.

5.3 SEGMENT IDENTIFICATION

In practice, if a pipe or other component breaks in a distribution system, the utility will first need to isolate this element by finding the closest set of isolation vales. The location of these valves will determine the spatial extent of the area affected while repairs are made. As defined by (Walski 1993), segments are the smallest part of the system that can be isolated by closing valves. The use of this concept to address the question of reliability has been implemented by some researchers who not only have considered the effect of valving in a shutdown but have also developed various automated algorithms for segment identification. These segment identification procedures have made use of diverse approaches including: the use of topological incidence matrices and depth search algorithms (Kao and li 2007; Loganathan and Jun 2007), identifying valves as pseudo-pipes (Giustolisi et al. 2008), the use of topological valve matrices with valves introduced as fictious pipes (Giustolisi and Savic 2010),the use of modified hydraulic equations (Creaco et al. 2010), and the use of an auxiliary valve matrix and vector to avoid the need for artificial pipelines (Alvisi et al. 2011).

The segment identification procedure adopted by the author in this paper is described in detail in Chapter 3 This segment identification method uses an existing EPANET network file structure where isolation valves have already been included. Thus, there is no additional processing of the network to create temporary fictional elements. The procedure launches a search from a junction node and travels through all the available paths, alternating between nodes and links only stopping when an isolation valve or dead end is reached. The group of elements found during the search and confined by the valves is considered a segment; then a new search is initiated departing from an unvisited node until all elements are checked. To execute this search the method requires a link-node incidence matrix to represent the network. A matrix populated by zeros (i.e. not incident) and ones (i.e. connected) representing how all the node elements (i.e. junction nodes, valve nodes, reservoirs, tanks) and link elements (i.e. pipes, pumps, valve links) are connected to each other is first constructed. The final result of the segment identification procedure will include: the total number of segments present in the network, the list of node and link elements constituting each segment, as well as the valves that would need to be closed to isolate them.

5.4 UNINTENDED ISOLATION

By incorporating the concept of a segment, it can be recognized that the closure of one segment may disconnect other parts of the network. Such disconnect parts are defined as unintended isolations. These unintended or secondary isolations can occur when the shutdown of the initial segment containing a pipe or component failure separates one or more additional segments from an available supply source. Analogous to the segment identification, several procedures to identify these secondary isolations have also been suggested by researchers (Loganathan and Jun 2007; Kao and Li 2008; Creaco et al. 2010; Gao 2014). For instance, Loganathan and Jun (2007) detect the unintended isolations by taking advantage of a segment-valve topology, where a segment-valve incident matrix is used with a breadth first search to trace the paths between segment and sources after a closure. The segment-valve topology, first introduced as arc-node topology by Walski (1993), involves a transformation of the traditional junction-link topology used for water distribution networks.

Recall that the distribution system can be defined as a graph $G = (V, E)$, where the V elements are the junctions and the E elements are the links of the graph G. Using the segments identified in the network and the valves required to isolate each segment, the system can be redefined using a segment-valve topology as graph $H = (S, IV)$, where the S elements are the segments and the IV elements are isolation valves for each segment. Representing this new graph as a diagram will result in the segments being represented as nodes and the isolation valves as links (or arcs). An example of this transformation is presented on Figure 5-1. Loganathan and Jun (2007) use this new representation to build an incident matrix for the valves and segments, which can then be used for the path search.

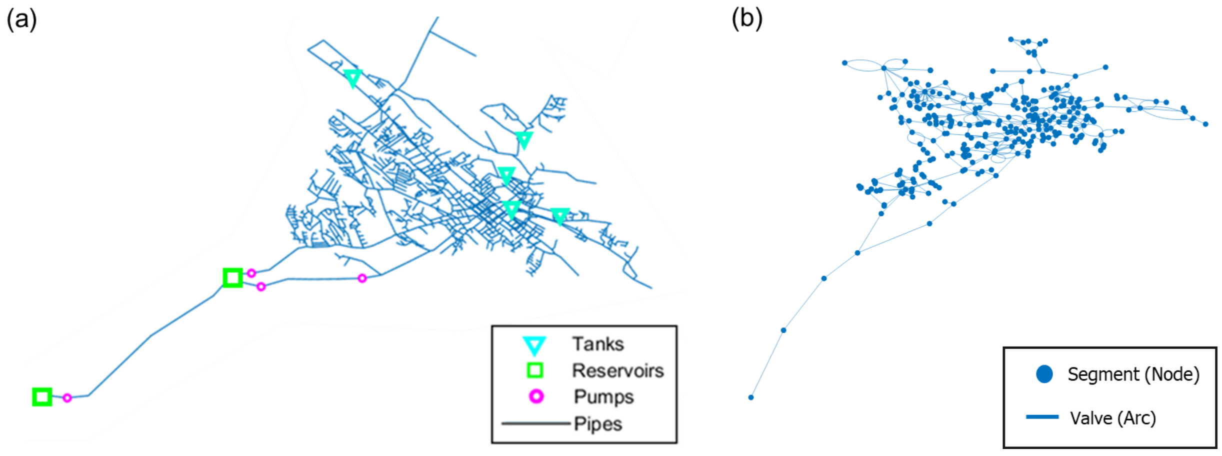

Figure 5-1 System KY8 in (a) link-node topology and (b) arc-node topology

In this paper the algorithm used for the identification of intended isolations is described by Chapter 3. This algorithm uses a segment-segment incident matrix to determine the secondary isolations linked to each segment closure. This secondary isolation identification algorithm performs a search of the available paths from the remaining sources using a series of matrices derived from the original segment-segment incident matrix. The segments that cannot be reached when the search is completed are defined as the unintended isolations for the initial closure. The search procedure can be repeated for all segment shutdowns and available sources, which will then result in a list of unintended isolations caused by each segment closure.

5.5 ALGORITHM for VALVE PLACEMENT

The problem formulated in this paper seeks to define the valve locations that would contribute to improving the reliability of the water distribution system as defined by the ability to provide service during a time period. Other researchers have approached this problem using diverse methods. Bouchart and Goulter (1991) added new valves to the length of the pipe to reduce the sections that need to be isolated. These valves were placed in the link that had a higher expected deficit in supply when failed, while assuming most links already had isolation valves at each of their ends. On the other hand, Ozger and Mays (2005), took on the valve optimization problem using a simulated annealing algorithm (or biased random walk). In this method valves are added around randomly selected junctions. Then a single valve is removed from a pipe around the same junction. The reliability is calculated to determine if this is an acceptable solution or if a new solution should be generated. Alternatively, Creaco et al. (2010) and Giustolisi and Savic (2010) made use of a binary genetic algorithm to obtain an optimal distribution of valves across the network. The former makes use of a modified version of the NSGAII (Deb et al. 2002), which uses integers for the values of each of the genes. Each integer value can represent a pipe without a valve, one valve near one of the ends, or valves at both ends. In this case the authors minimized the total valve cost and the demand shortfall. The objective function for this formulation aimed to minimize the total number of valves and the size of the largest segment.

For this research, the author approaches the problem using a heuristic method that employs graph theory concepts. While the algorithm may not guarantee a global optimum solution, it does provide an improved solution in a reasonable computational time frame. In formulating the problem statement to be solved by the algorithm, two different types of objective functions are examined: one which minimizes the maximum number of valves associated with any segment and one which minimizes the maximum water supply demand lost as a result of the shutdown of any segment. The later objective is quantified using a simple topological metric (TM). This metric considers the isolated segment and unintended isolations in estimating the relative shortage in supply that results from a segment isolation. This metric can be expressed as:

$$\mathrm{TM}_s = \frac{Q_T - Q_{R_{TM(s)}}}{Q_T} = \frac{Q_{TM(s,1)} + Q_{TM(s,2)}}{Q_T} \tag{5-1}$$

$$Q_T = \sum_{\mathrm{i}=1}^{n} q_i \tag{5-2}$$

$$Q_{R_{TM(s)}} = \sum_{\mathrm{j}=1}^{m(s)} q_j \tag{5-3}$$

where TM_s = the topological metric for segment s, s is the segment number, n is the total number of demand nodes in the network, q_i is the demand at node i, Q_T is the total demand allocated to the network, $Q_{R_{TM(s)}}$ is the demand that can be fulfilled when the segment s has failed, and $m(s)$ are the nodes which continue to operate under the failure of segment s. Further, $Q_{TM(s,1)}$ is the shortage experienced in the network as the direct result of the shut-off for segment s and $Q_{TM(s,2)}$ is the shortage due to unintended isolations.

Valves have been traditionally recognized as practical methods to increase the reliability of a system (Bouchart and Goulter 1991; Walski 1993; Mays 2000), even when their use in reliability assessments and optimization has been more limited. More valves reduce the size of the network subsections (i.e. segments), typically reducing the number of customers out of service. However, it is important to consider that some larger segments may have lower supply shortages than those associated with the failure of comparably smaller segments. This may be the case if a smaller segment has a higher costumer density, an elevated volume requirement, or a number of high impact secondary isolations. Furthermore, if a smaller segment provides service to a critical customer it may be a higher priority for the utility. Because of this, simply increasing the number of valves may not be as effective or cost efficient as reconfiguring a targeted set of segments. Although the general recommended number of valves to close a segment is typically 4 (Ozger and Mays 2005), the actual valve placement in water distribution network often leads to a number of valves that exceeds this recommendation. In addition, most systems contain a limited number of internal valves (i.e. valves that cannot be used to isolate a subsection when closed) which then adds to the total. While previous optimization approaches have highlighted the total number of isolation valves employed in the optimal designs produced, little information has been provided about the configuration of the individual segments. The design procedure proposed by the author employs a two-step heuristic to 1) first determine which the set of segments to target for improvement, and then 2) determine the optimal distribution of valves within that segment.

The proposed heuristic method seeks to improve the reliability of the water distribution system by effectively reducing the size of existing segments by adding isolation valves to the network. This can be done to minimize the maximum number of valves associated with any given segment (e.g. no segment can contain more than 5 valves) or to reduce the value of the topological metric associated with any segment (e.g. no segment can have a TM > 5%). The algorithm first starts by ranking the segments based on one of these two objectives, and then continues by systematically and sequentially operating on each segment until the objective for that segment is satisfied. Once the criteria for that segment has been satisfied, the algorithm then moves onto the next segment and so on until all segments have met the specified criteria. Regardless of the overall objective (i.e. minimize TM or minimize the maximum number of valves per segment, the underlying segmentation algorithm is the same and can be summarized as follows:

1. Initiate the segment identification procedure and compute the segment-based assessment.
2. Identify a candidate segment for reconfiguration

3. Eliminate periphery links with existing valves.
4. Decompose the segment into biconnected components.
5. Create a block cut tree for the current segment.
6. Identify number of possible reconfigurations for the candidate segment
7. Identify the number of isolation valves required for each reconfiguration.
8. Rank the possible segment reconfigurations for the current segment and select a placement option.
9. Initiate a new segment identification analysis and compute a new segment-based assessment metric (e.g. estimate TM) for the network with the new valve.
10. Check termination criteria.

Each of these steps will be explained in more detail in the following paragraphs along with a simple example illustrating the process.

Step One. Initiate the segment identification and compute segment-based assessment

The segment identification procedure (Chapter 3) and the segment-based assessment algorithm (Chapter 4) were constructed using the MATLAB EPANET Toolkit (Eliades et al. 2016), which makes use of the open source EPANET (Rossman 2000) hydraulic engine. The only input required to initiate the identification and assessment algorithm is an EPANET compatible input file (i.e. *.INP). The network model should already include the existing layout of isolation valves in the system. The segment identification and assessment process does not require additional inputs from the user and avoids assumptions on valve placement. It uses the actual element locations as recorded in the network file without requiring the addition of pseudo-links or auxiliary elements.

Once the segment identification procedure is completed, the number of segments in the network and their configuration is recorded. Next a segment-based assessment reliability metric is computed. In this particular application, the topological metric (Eqs. 1-3) is used. The assessment algorithm sequentially fails each of the identified segments and then identifies the resulting supply shortfall associated with each isolation. These results are then used to evaluate the topological metric for each segment. These results can then be ranked and thus used to identify which segments cause the greatest overall shortfalls (Figure 1). At the same time, the number and IDs of the valves needed to isolate each segment can also be identified. In the end, both sets of information can be used to prioritize which segments to subsequently partition.

Application of the segment identification and assessment algorithms for an example network (i.e. KY8) in the University of Kentucky Water Distribution Research Database (Hernandez et al. 2016)are presented in Figure 2. Notice that the histogram in Figure 5-2(b) shows the results for the topological metric for both primary and secondary isolations with the number of valves required to isolate that segment displayed atop the histogram (e.g. V=14 for segment 49).

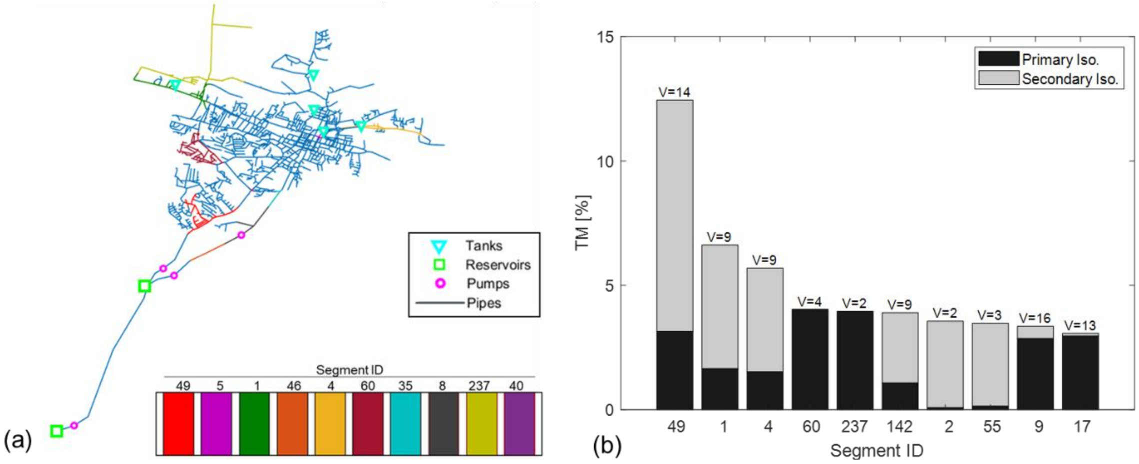

Figure 5-2 (a) Schematic for KY8 with highlighted critical segments and (b) Topological Metric results for KY8

Step Two. Identify a candidate segment for reconfiguration

Once the topological metric and the total number of required isolations valves required to isolate each segment have been identified, this information can then be used to prioritize which candidate segment to select for further segmentation, with the realization that additional segmentation (through the addition of new isolations valves) will result in a lower supply shortfall and reduce the total number of isolation valves associated with a given segment.

The criteria to define the candidate segment will depend on one of two different objectives: (1) minimizing the demand shortfall and (2) reducing the number of isolation valves required for segment closure. In the case of the objective of (1) the candidate segment selected will be the segment with the current highest observed TM score. Since the topological metric is directly related to the supply shortfall, reconfiguring the segment that creates the largest deficit should provide an increase in the overall reliability level. On the other hand, in the case of the objective of (2) the candidate segment will simply be the one that requires the largest number of valves for an effective closure. As can be seen in Figure 1 for KY8, these two metrics do not necessarily produce the same priority ranking of segments. Thus, both metrics are considered independently in the application study. In applying objective 1 to KY8, segment 49 (with at topological metric of 13%) would be the first segment selected for further segmentation. In applying objective 2 to KY8, segment 9 (with 16 valves) would be the first segment for further segmentation

Step Three. Eliminate periphery links with existing valves

Once a candidate segment has been selected the algorithm continues by examining the junction nodes and pipe elements in that segment. This information can be retrieved from the results of the segment identification procedure. Recall that new valves will only be placed on existing pipelines. This means that all the pipe elements included in the segment may be possible locations for a new valve. Still, the solution space can be reduced by pruning all periphery links that already contain an existing isolation valve. As a result, a simplified list of elements for the candidate segment will be produced (i.e. a reduced segment) only including the link and node elements that are not already connected to an isolation valve. This step is illustrated in Figure 3, using segment 49 from KY8. In this case, the links already containing isolation valves are shown in bold Figure 5-3(a). Once identified, the algorithm then eliminates each of these links to generate a new reduced segment which now contains the complete set of pipe links in which an additional isolation valve can be added (see Figure 3(b)).

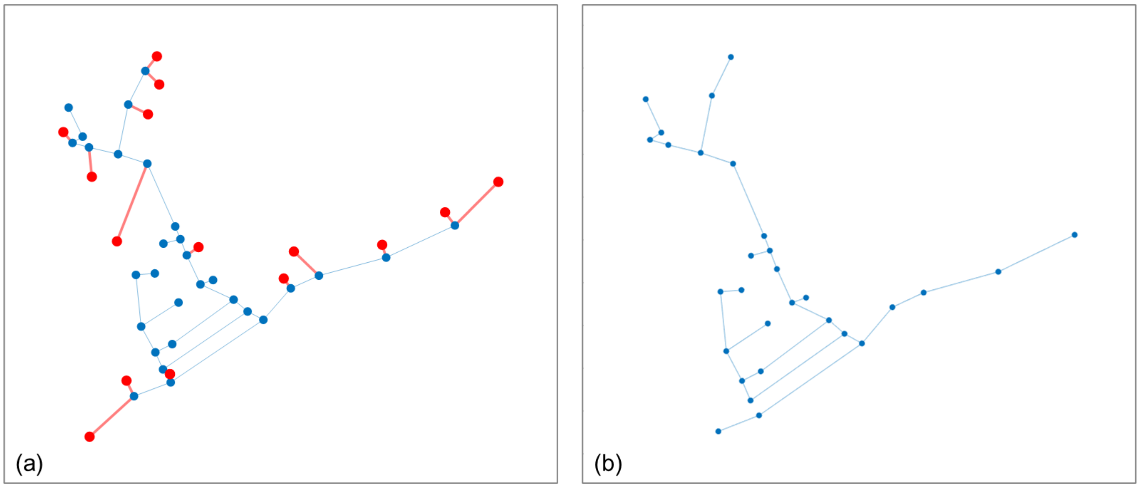

Figure 5-3 (a) Segment 49 from KY8 and (b) Reduced Segment 49

Step 4. Decompose the segment into biconnected components

The identification of the “best” link to add a new isolation valve so as to minimize the selected objective function can be facilitated by representing the existing segment as an associated junction link topology graph (i.e. as a graph $G = (V, E)$). This is done so as to allow its decomposition into discrete subcomponents and allow the identification of the existing cut points (i.e. cut vertex, articulation points).

A cut point (or an articulation point) in an undirected graph G is a vertex v ($v \in V$), such that the removal of v with its edges splits the network into two or more components. Thus, the use of articulation points can provide guidance on the possible locations of isolation valves in order to effectively reconfigure a candidate segment. In lieu of the more complicated Segment 49, a simpler graph (see Figure 4) is used to illustrate the concept.

From undirected graph theory (Diestel 2017), a component is defined as a maximal connected subgraph, while a graph is considered connected if it is a non-empty collection of elements and any two of its vertices can be linked by a path. Any graph can thus be decomposed into its biconnected components to reveal the articulation points, since these will be the vertices belonging to multiple components. Note that a biconnected component of a graph is a maximal biconnected subgraph (i.e. if a vertex were to be removed from the biconnected subgraph it will remain connected). Computing the biconnected components in the reduced candidate segment will thus lead to the identification of the existing cut points and thus potential locations for new isolations valves.

Consider the initial distribution network G, that can also be represented as a graph $H = (S, IV)$ using the segment-valve topology. Now, identifying a segment x as the candidate (i.e. $S = x$) segment for reconfiguration, define this subsection of the graph G as $G_x = (V_x, E_x)$ where the V_x elements are the junction nodes (or vertices) of the subgraph G_x (i.e. $G_x \subset G$) and the pipe elements (or edges) are the elements of E_x. After the completion of Step Three (see above) this subgraph G_x is reduced to only include the candidate pipe elements for valve placement (E_x') and their respective junction nodes ($V_x{}'$). This reduced subgraph can be defined as $G_x' = (V_x{}', E_x')$. It is the reduced subgraph that will be used to compute the biconnected components. For illustration purposes the graph presented on Figure 4 (a) will be assumed to represent the graph of the reduced candidate segment (G_x').

Using a search algorithm, the biconnected components of the network are identified (see Figure 5-4 (a)) and labeled BC1 – BC6. Each biconnected component of G_x' will include a series of pipe links and junction nodes (see Figure 5-4(b)). No edge can be in two or more biconnected components of the graph G_x', while two biconnected components in the same graph will not have more than one vertex in common (Figure 5-4). The vertex that two or more biconnected components have in common is a defined as a cut point or a cut node. Observe Figure 5-4(a) that for the example network the edges of each biconnected component are designated by a different color, while the cut vertices have been enlarged. At this point the cut points of the reduced segment G_x' can now be identified (see bolded nodes in Table 5-1), but a few more steps are necessary to use this information to define new plausible locations for isolation valves.

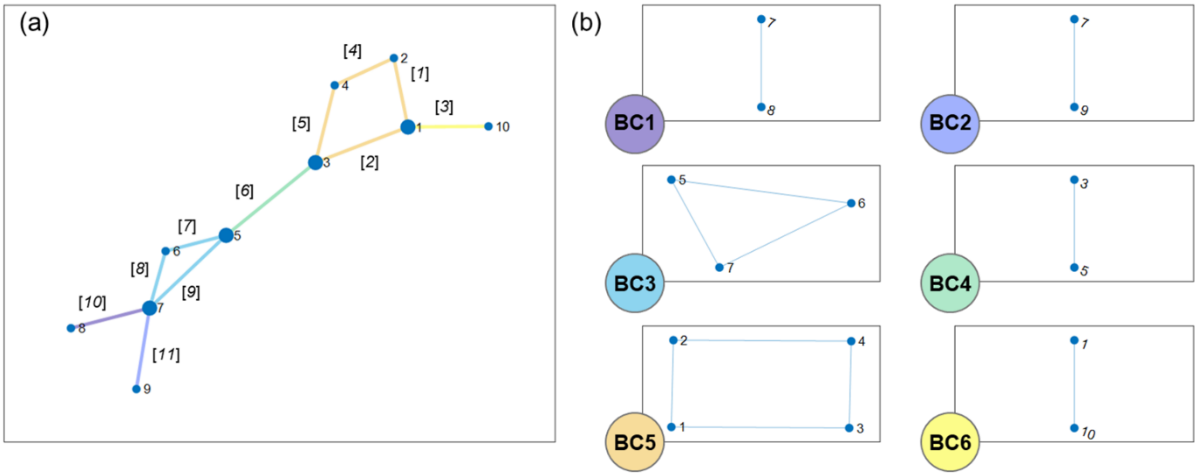

Figure 5-4 (a) Example Network Identifying Cut Nodes and (b) Biconnected Components

Table 5-1 Biconnected Components for Example Network

Biconnected Component (Block)	Junction Nodes (Cut nodes in bold)	Pipes (Links)
BC1	**7**,8	P10
BC2	**7**,9	P11
BC3	**5**,6,**7**	P7,P8,P9
BC4	3,**5**	P6
BC5	**1**,2,**3**,4	P1,P2,P4,P5
BC6	**1**,10	P3

Step 5. Create a block cut tree for the current segment

Once the different biconnected components (or blocks) and the associated nodes and cut vertices have been identified, the network (or undirected graph) can be transposed into block cut tree (see Figure 5-5(b)). In this graph each of the cut nodes is connected by a single line or a cord (e.g. C1) to the components to which they belong (in this illustration, the cut points are the represented by discs with more than one color or shading). This transposition of the link-junction graph into a block cut tree represents the cut points of the reduced segment as a multi-colored disc and the group of elements (i.e. Pipe elements and junctions nodes) of each biconnected component (see Figure 5-4(b)) as a separate single color disc (see Figure 5-5). The block tree now provides information on how each cut node (i.e. the multi-colored disc) is connected to the rest of the elements (i.e. how elements will be separated upon the removal of the cut point). This analysis can be applied to any candidate segment. The equivalent diagram for Segment 49 in KY8 is presented on Figure 5-6.

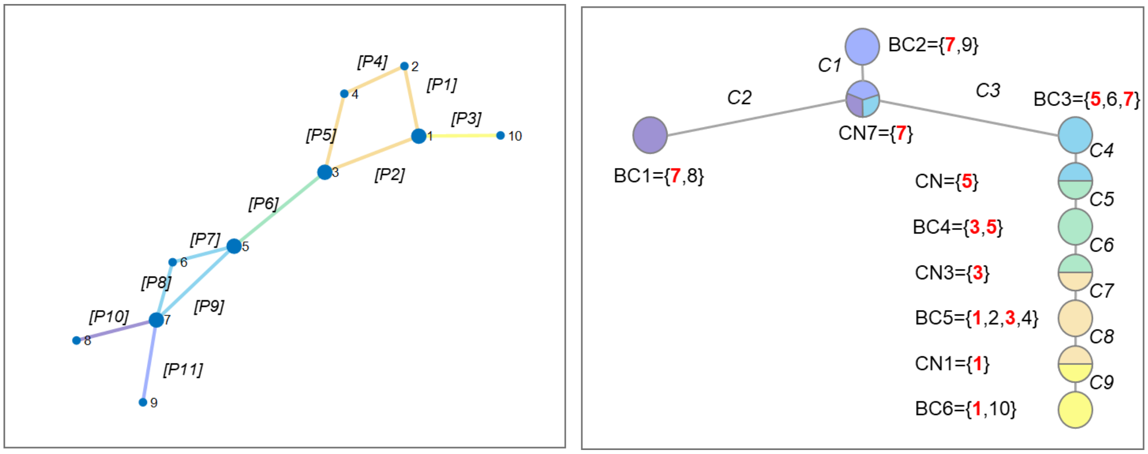

Figure 5-5 Example Graph in Link-Junction Topology and (b) Block-Cut Tree

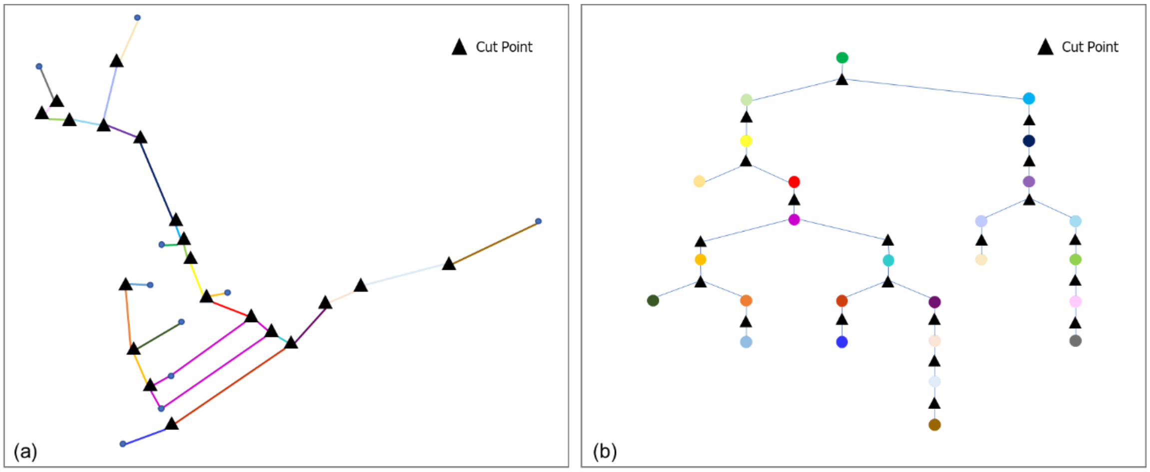

Figure 5-6 KY8 Segment 49 Graph in Link-Junction Topology and (b) Block-Cut Tree

Step 6. Identify number of possible reconfigurations for the candidate segment

Once the block cut tree for the segment has been created, it can now be used to identify the number of viable cut locations that would effectively split the candidate segment into two segments and thereby reducing the total affected supply demand. Observe in Figure 5-6 (b) that each cut node/cut point (i.e. the triangles) may be connected to several different blocks/biconnected components (i.e. the discs) by single line segments (called cords). Each of these cords will now indicate a possible way to reconfigure or the subdivide the segment by making a cut (i.e. add isolation valves).

However, this does not mean that each cut node and the subsection of the network represented by the block are connected by a single pipe element. The cord in the block-cut tree denotes that the cut point belongs to the set of the biconnected components grouped in the block to which it is associated to (e.g. in Figure 5-5 (b) the cord C1 indicates the CN7 belongs to the biconnected component BC2).

Once the block cut tree has been constructed, the number of potential options to subdivide the candidate segment can be identified. This is accomplished by examining each cut point and then by recording each connecting cord and the associated block on the other end of that cord (i.e. not the cut node). For the example network shown in Figure 5-4 and Figure 5-5, there are four cut nodes in the network (i.e. cut nodes CN7, CN5, CN3, and CN1). For simplicity, each cut node has been assigned an ID number which corresponds to the junction node ID in its associated junction-link representation. The cords and associated blocks (or biconnected components) associated with each cut node are summarized in Table 5-2. Removing each of the cords creates a subdivision, representing a different 'cut' in the network. However, since each cord does not strictly represent a pipe element from the candidate segment, it just denotes the relation between cut points and blocks, the specific number of valves required to effective close each new subdivision will require more information. First, however, the algorithm identifies all of the possible segment reconfigurations that are possible and then ranks them on their ability to provide an equal division of the segment demand. This is done by first evaluating each cord.

Table 5-2 Block-Cut Tree Cut Nodes with Associated Cords and Non-Cut Node Blocks

Tree Cut Node	Cord (Non-Cut Node Blocks)
CN7	C1(BC1), C2(BC2), C3(BC3)
CN5	C4(BC3), C5(BC4)
CN3	C6(BC4), C7(BC5)
CN1	C9(BC5), C9(BC6)

The IDs for the block and cut node associated to each cord are identified by the algorithm, starting with the first cord (e.g. C1) and moving sequentially through the list of the remaining cords until the last cord (e.g. C9) is examined and evaluated. The results for this procedure on the example network are illustrated on the first three columns of Table 5-3.

Next, it is possible to take advantage of the block-cut tree representation and the cords identified to determine how the demands would be distributed with each possible segment split. This is accomplished by performing a breadth first search beginning with the cut node that was attached to the removed cord (i.e. Sub-tree Rooted in Cut Node). Once that set of blocks has been identified, the remaining blocks on the other side of the cord will simply be the rest of the blocks in the graph (i.e. Sub-tree Rooted in Non-Cut Node Block). Note that the demands of the cut points are not included in the allocated demands of each block to avoid double counting. For instance, this means the demand for Junction Node 1 will only be allocated to CN1 and not the blocks BC5 or BC7. A summary of the blocks associated with each cord for the example graph in Figure 5-4 is provided in Table 5-3.

Table 5-3 The Associated Cut Node and Cut Node Blocks Associated with Each Cord

Cord	Cut Node	Non-Cut Node Block	Sub-tree Rooted in Cut Node	Sub-tree Rooted in Opposing Non-Cut Node	Demand Split
C1	CN7	BC1	CN7,BC2.BC3,CN5,BC4,CN3,BC5,CN1,BC6	BC1	90/10
C2	CN7	BC2	CN7,BC1,BC3,CN5,BC4,CN3,BC5,CN1,BC6	BC2	90/10
C3	CN7	BC3	CN7,BC1,BC2	BC3,CN5,BC4,CN3,BC5,CN1,BC6	30/70
C4	CN5	BC3	CN5,BC4,CN3,BC5,CN1,BC6	BC3,CN7,BC2,BC1	60/40
C5	CN5	BC4	CN5,BC3,CN7,BC2,BC1	BC4,CN3, BC5,CN1,BC6	50/50
C6	CN3	BC4	CN3,BC5,CN1,BC6	BC4,CN5,BC3,CN7,BC2,BC1	40/60
C7	CN3	BC5	CN3,BC4,CN5,BC3,CN7,BC2,BC1	BC5,CN1,BC6	60/40
C8	CN1	BC5	CN1,BC6	BC5,CN3,BC4,CN5,BC3,CN7,BC2,BC1	20/80
C9	CN1	BC6	CN1,BC5,CN3,BC4,CN5,BC3,CN7,BC2,BC1	BC6	10/90

The two lists of cut node blocks associated with a given cord can now be used to determine the distribution of the split of the total segment demand with each cord, since the set of junctions associated with each block is known (see Figure 5-4(b)). For instance, consider the removal of Cord C5 from the block-cut tree of the example network. This splits the tree in two, separating the cut node CN5 and block BC4 (Figure 5-7(b)). This then divides the segment into two sub-trees, one rooted in CN5 containing BC3, CN7, BC2, and BC1, with the other subtree rooted in BC4 containing CN3, BC5, CN1, and

BC6 (see Table 5-3). If one were to assume that each junction node has the same demand (Figure 5-4(a)), then 50% of the segment demand would be associated with the subtree rooted in CN5, while the remaining 50% of the segment demand would be associated with the remaining subtree rooted in BC4. This would mean that cord C5 yields a demand split of 50/50. Using the same approach, the demand splits for each cord can now be determined (see Table 5-3). If for some reason the demands are not uniform (which would be the normal case), then the distribution can be directly obtained by simply adding up all the demands associated with the blocks (i.e. the junction nodes belonging to each biconnected component without the demand allocation of the cut points) and the cut nodes.

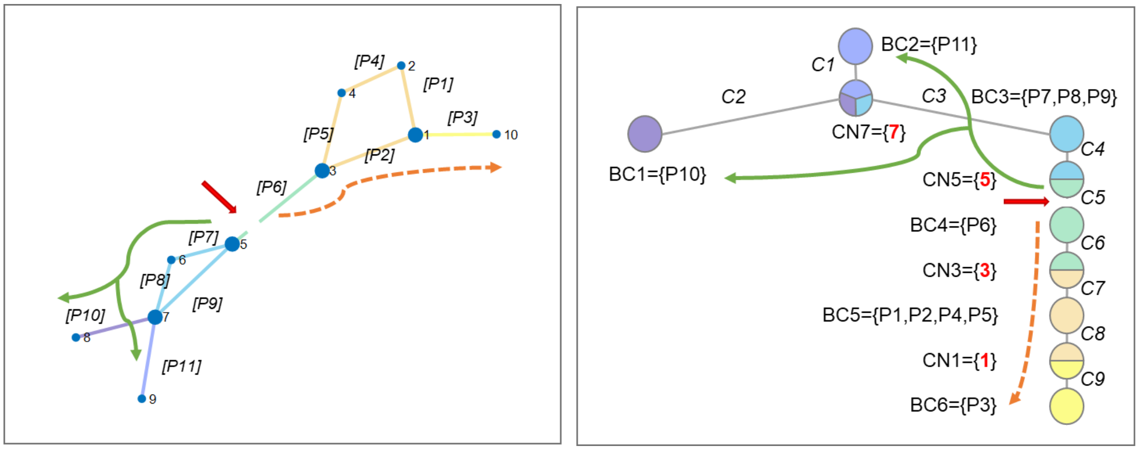

Figure 5-7 (a) Example Graph in Link-Junction Topology and (b) Block-Cut Tree with Removed Cord C5

Step 7. Identify number of isolation valves required for each reconfiguration.

To this point the algorithm has defined several general ways that the candidate segment can be subdivided (i.e. indicated by each of the cords in the block-cut tree), still the pipes where valves should be placed to effectively create another subsection have not been found. To identify these pipes, the algorithm will continue use the block-cut tree and review identified how the elements from the reduced candidate segment were mapped into it.

First, revisit the list of cut nodes and retrieve the element IDs from the cut points that corresponds to the link-node representation of the candidate segment (G_x'). For instance, consider the cut node CN5 in the block-cut tree is Junction Node 5 on the initial graph (Figure 5-5(a)). In this example the label for each cut node already indicates the ID of the Junction Node form the link node topology (i.e. CN#). Note that a possible option to effectively subdivide the candidate segment into smaller portions would be to valve all the pipe elements connected to the junction node that has been identified as a cut point (e.g. Junction Node 5 in the example used), However, this would violate our desire to do this with as few as valves as possible. In order to achieve this objective, and additional step is employed.

First, for a given cord, identify the cut node and the non-cut node block linked to it (e.g. as shown in Table 5-3, CN5 and BC4 are at opposite ends of cord C5). Next, identify which of the pipes are incident to the Junction Node identified as a cut point being analyzed. For instance, using CN5 which represents Junction Node 5, we can now use Table 5-3 to identify which pipes belong to BC4 and which are also linked to CN5. In this case there is only one pipe, P6, which is connected to Junction Node 5. Observe, that if a valve were to be placed on this pipe P6 the candidate segment can be effectively subdivided (Figure 5-7(a)), creating the equivalent condition to the segment ‘cut’ illustrated by the removal of C5 from the block-cut tree in Figure 5-7(b). This means, that in reconfiguring the segment represented by the removal of each cord in the block cut tree, a split can be created by placing valves only on the pipes belonging to the block that was connected to a cut point by the current cord being examined. Likewise in Table 5-3, we note that cord C4 connects cut node CN5 and non-cut block BC3. Thus if we split block-cut tree at cord C4, this will mean that we can split the segment by placing valves in those pipes that are connected to the associated cut node (i.e. N5) and are contained in block BC3. In this case, this would require us to place valves in both P7 and P9. However, both solutions will be superior to one in which valves are placed in all pipes connected to the Junction Node associated with the cut node (i.e. Junction 5). The later would thus require valves to be placed in pipes P6, P7, and P9.

The ultimate decision of where to place the isolation valves is decided by two criteria: 1) pick a solution in which the demand split is as close to 50/50 as possible, and 2) pick a solution with as few of valves as possible (i.e. one valve is preferable to two valves). For example, each cord connected to a cut node and a block represents a different segment reconfiguration. As shown previously in Table 5-3, each of the resulting splits are associated with different demand distributions. For example, observe both cord C6 and cord C7 will both result in a 60/40 demand split, but only one valve will be required is required in the case of C6 (i.e. placed in pipe P6) while two isolation valves are required in the case of C7 (placed in pipes P2 and P5). Thus, all things being equal, a valve in P6 would be preferable to two valves in P2 and P5.

In order to facilitate this decision, the algorithm evaluates each cord, determines the associated cut node and non-cut node block, and then identifies all pipes in the non-cut node block that are connected to the cut node. Each of these pipes will thus identify a potential valve location. A summary of the results of this process are provided in Table 5-4.

Table 5-4 Location and Number of Isolation Valves Required for Possible Segment Reconfigurations

Cord	Cut Node	Non-Cut Node Block	Possible Valve Location	Number of Valves
C1	CN7	BC1	P10	1
C2	CN7	BC2	P11	1
C3	CN7	BC3	P8,P9	2
C4	CN5	BC3	P7,P9	2
C5	CN5	BC4	P6	1
C6	CN3	BC4	P6	1
C7	CN3	BC5	P2,P5	2
C8	CN1	BC5	P1,P2	2
C9	CN1	BC6	P3	1

Step 8. Rank the possible segment reconfigurations for the current segment and select a placement option.

To this point, several reconfiguration options have been examined, since each cord in the block-cut tree can be interpreted as a unique valve placement to subdivide the candidate segment. For each cord and its associated cut node the demand split, and the number of valves required are thus known.

As mentioned previously, the algorithm has been set up to prefer a valve placement that will be able to provide a split close to a 50/50 demand allocation using the fewest number of valves, ideally a single valve. In order to guide this process a priority score is assigned to each cord. This score can be calculated using the information on the demand split for each identified cord calculated on Step 6 (see Table 5-3) and the number of valves required and their possible locations on Step 7 (see Table 5-4). This score will be the quotient of the demand split with the largest demand portion as the numerator multiplied by the number of valves required for the segment reconfiguration. For example, in the case of cord C1 this prioritization score will be $\mathrm{PS} = \left(\frac{90}{10}\right) \times 1 = 9$. The lowest prioritization score will be the valve placement selected, since the ideal reconfiguration will have a priority score of one (i.e. with 50/50 demand split and a single valve requirement. $\mathrm{PS} = \left(\frac{50}{50}\right) \times 1 = 1$). The results of this calculation for each cord for all the cords in the example network are summarized in Table 5-5. Based on these results, the solution associated with cord 5 (i.e. place a valve in pipe P6) is thus preferred solution for this segment.

Table 5-5 Prioritization Scores for Possible Segment Reconfigurations

Cord	Cut Node	Non-Cut Node Block	Demand Split	Possible Valve Location	Priority Score
C1	CN7	BC1	90/10	P10	9.0
C2	CN7	BC2	90/10	P11	9.0
C3	CN7	BC3	70/30	P8,P9	4.7
C4	CN5	BC3	60/40	P7,P9	3.0
C5	**CN5**	**BC4**	**50/50**	**P6**	**1.0**
C6	CN3	BC4	60/40	P6	1.5
C7	CN3	BC5	60/40	P2,P5	3.0
C8	CN1	BC5	80/20	P1,P2	8.0
C9	CN1	BC6	90/10	P3	9.0

Note that there could be some segments that may only have a single pipe link location available. If that is the case, then the valve will be simply be placed in that pipe element (i.e. the reduced candidate segment is a single pipe). Additionally, the structure of some segments may be intricately connected, and no usable cut points may be identified (e.g. the candidate segment cannot be decomposed into multiple components). This could mean the segment analyzed would require a much denser valving scheme (e.g. placing valves at all incident pipe links at each junction), Currently, the algorithm does not proceed in this manner, but simply highlights the segment for further examination or consideration by the utility.

Once a cut option has been defined (i.e. those enumerated by the cords in the block-cut tree) and the pipe location has been recorded (e.g. pipe P6 for the example candidate segment) the required number of valves are added to the network model of the water distribution system (i.e. graph G, the initial EPANET input file) at the specified location(s) and the network reevaluated.

Step 9. Initiate segment identification procedure, and compute segment-based assessment for network with new valving component.

Using the updated network model, a new segment identification procedure and assessment are executed. The assessment procedure followed is the same as the initial assessment. Since the optimization algorithm only considers the demand shortfall, only the module for the topological metric is be executed. However, note that as new valves are added some of the original segments will be split into smaller network subsections. For consistency, a suffix will be added to the segments to indicate if a new segment is a portion of a previously identified segment. For example, if Segment 1 is subdivided, the segment IDs for these new portions will be 1.1 and 1.2. This nomenclature will continue through the valve placement procedure, where if segment 1.1 is further subdivided the new units will be labeled as segment 1.1.1 and 1.1.2.

Step 10. Check termination criteria.

Recall that the two objective functions used require different termination criteria. In the case of (1) *minimizing the demand shortfall (as measured by the topological metric)* if all the segment shutdowns are below the threshold set by the user (e.g. $\mathrm{TM}_s \leq 5\%$) the process ends and the current valve distribution it is recorded as the final design. On the other hand, if there is a TM score that is above the set limit the system is examined again to find new viable candidate segments for reconfiguration and the process is repeated, going back to Step 2 for a new iteration. The procedure for the objective (2) *reducing the number of isolation valves required for segment closure* is equivalent, only this time the threshold set by the user will be a desired number of valves per segment (e.g. $\mathrm{NV}_s \leq 5$).

Observe that in some occasions, it is possible that the algorithm may encounter a segment that cannot be subdivided while still failing to fulfill the objective function (e.g.

TM above the limit, or a number of valves exceeds the target). This could occur under a couple of circumstances: 1) the segment does not have identifiable cut points or 2) the segment contains the only source in the system. Note that in the cases where no cut point was found several causes were identified: after the reduction there are no viable pipe elements remaining (e.g. an empty reduced segment), there is a single pipe available, or the reduced segment has a grid like structure. Each of these cases are examined in detail below.

If an empty reduced segment is encountered, there are no available locations for valve placement. Thus, this segment is flagged and skipped as a viable candidate segment in future iterations. On the other hand, if a reduced segment still contains a single pipe, the valve is simply placed at this location. Then, the algorithm can proceed to perform a new assessment and check the termination criteria. For instance, observe that the segment depicted in Figure 5-8(a) requires six valves, yet the reduced segment contains a single pipe element (Figure 5-8(b)).If this segment were to be evaluated using the limit for $NV_s \leq 5$ objective, an additional reduction in the number of valves would be required. However, in this case there are no cut points. Nonetheless, the remaining location is still viable, and an isolation valve could be installed in the remaining pipe.

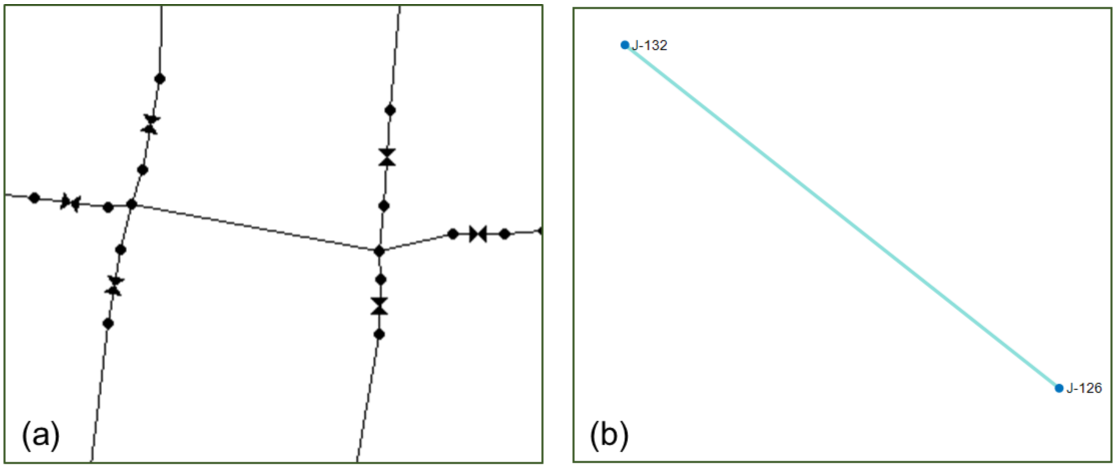

Figure 5-8 (a) Schematic for Segment with NV=6 and (b) its Reduced Segment

Finally, consider the case of an associated segment that was ultimately reduced to a grid of two blocks as shown in Figure 5-9(a) in which none of the associated the interior nodes constitute a cut node. As a result, the algorithm would not be able to further reduce the segment. However, at this point, if at least one additional valve were to be placed randomly on any of the interior pipes, then additional cut points will naturally emerge, which will then allow the algorithm to continue. For example, if a valve is placed in pipe *[2]* then nodes 5 and 6 become cut nodes (see Figure 5-9(c)) which would then be associated with three different non-cut blocks: CN5 would be associated with BC1 and BC2, and CN6 would be associated with BC3 and BC2. Application of the methodology to these cut nodes would thus yield four possible valve locations in pipes *[4]*, *[5]*, *[6]*, *[7]*. Selection of the option to place a valve in pipe *[7]*, which would satisfy the criteria to subdivide the segment as evenly as possible using one valve, would then split the segment into two new segments, one fully containing pipes *[1]*, *[3]*, *[4]* and *[6]*, and one containing pipe *[5]*. The same protocol could then be applied to further reduce the first four pipe segment, while the second segment would now correspond to the single pipe scenario discussed above.

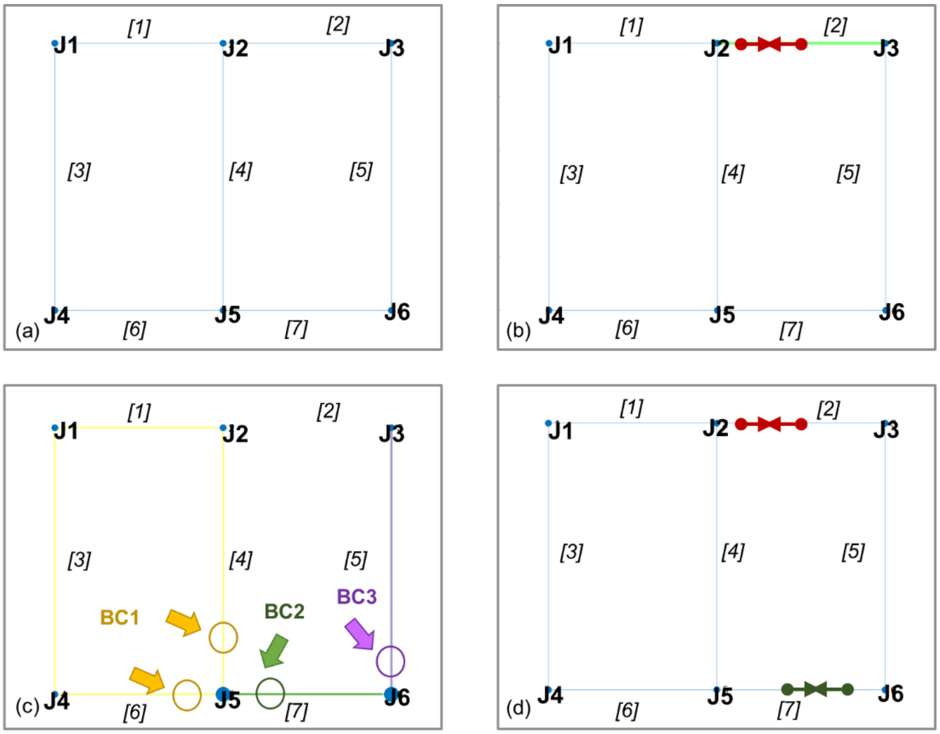

Figure 5-9 (a) Two Block Grid Associated with Reduced Segment, (b) Internal Valve Added at a Random location, (c) Highlighted Cut Points for Reduced Segment and Possible Valve Locations, (d) Final Reconfiguration for Reduced Segment

5.6 CASE STUDY

To test the efficacy of the proposed valve placement method, it was applied to a small water distribution system in the state of Kentucky (see Figure 5-10). The base model used is KY6 (Hernandez et al. 2016)which has been updated to include the locations of the existing isolation valves and hydrants as collected by a recent survey of the area. The system contains 811 pipes, 1401 junction nodes, 235 hydrants, 346 isolations valves, and 1156 pipe elements. A pipe element is a fractional section of pipe that is created when an isolation valve attached to a pipe is closed. Additional details about the system can be obtained from the University of Kentucky Water Distribution Systems Research Database (https://uknowledge.uky.edu/wdsrd/). The application of the segment identification methodology in Chapter 3 to the EPANET (Rossman 2000) data file of the system resulted in 256 segments. Details on the top ten most critical segments are shown in Table 5-6.

Figure 5-10 System KY6 Schematic

Table 5-6 Statistics of the Top Ten Critical Segments in KY6 (TM metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Sec. Pipe Elements	Total Sec. Length [ft]	Sec. Isolated Nodes	Total Isolated Nodes
13	22	111	22080	110	7	13	2418	20	130
23	14	55	21264	55	17	54	20535	71	126
10	20	61	11603	61	8	8	2205	16	77
25	11	36	7032	37	5	11	2060	16	53
184	5	27	10041	28	4	14	5611	18	46
217	4	5	13991	6	6	23	12519	29	35
216	2	1	170	2	5	22	12349	27	29
143	2	4	4588	5	3	15	7020	18	23
140	2	3	741	4	4	19	11608	23	27
76	6	14	2645	15	3	14	2773	17	32

5.7 RESULTS

In applying the valve placement heuristic to KY6, the algorithm first ranks and prioritizes all the segments on the basis of either the maximum TM score or the maximum number of valves. Based on the selected criteria, the algorithm then applies the valve placement methodology sequentially, one segment at a time, until the current segment under consideration meets the selected solution objective (as a result of the addition or one or more valves). Once that segment has been completed, the algorithm then goes onto the next segment in the list until all the segments have met the selected solution objective. In each iteration, the algorithm seeks to split the total segment demand as evenly as possible within the segment by placing as few new valves as possible.

In applying the valve placement heuristics to KY6, three different solution objectives were used, one associated with a maximum TM score (i.e. $\mathrm{TM}_s \leq 5\%$) and two associated with the maximum number of isolations valves (i.e. $\mathrm{NV}_s \leq 10$ and $\mathrm{NV}_s \leq 5$). Summary results of the valve placement heuristic as applied to KY6 for the three different placement objectives are also shown in Table 5-7. Detailed statistics on the top ten ranked segments (by the TM metric) for each of the three-valve placement objective results are provided in Table 5-8-Table 5-10. Additional histogram plots of the TM metric for each solution as well as the distribution of valves among the segments are provided in Figure 5-11.

Table 5-7 Summary Statistics for KY6 and Final Results of Case Study Application

	KY6		**KY6 (TM≤5%)**		**KY6 (VN≤10)**		**KY6 (VN≤5)**	
TM_max (Segment ID)	13.38%	(**13**)	4.83%	(**10.2**)	7.08%	(**23.1**)	3.38%	(**184**)
TM_avg (Segment ID)	0.62%	(All)	0.60%	(All)	0.60%	(All)	0.50%	(All)
Segments	256		264		265		315	
Number of Valves	346	(All)	354	(All)	356	(All)	408	(All)
Number of External Valves	320	(All)	338	(All)	339	(All)	402	(All)
Number of Internal Valves	26	(All)	16	(All)	17	(All)	6	(All)
Max.Valves per Segment (Segment ID)	22	(**13**)	14	(**10.1**)	10	(**25.1**)	6	(**10.1.1.1.1**)
Min.Valves per Segment	1		1		1		1	
Avg.Valves per Segment	1.3	(All)	1.3	(All)	1.3	(All)	1.3	(All)

Table 5-8 Statistics of the Top Ten Critical Segments in KY6 (TM metric) with Objective TM5%

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Sec. Pipe Elements	Total Sec. Length [ft]	Sec. Isolated Nodes	Total Isolated Nodes
10.2	12	37	7108	37	2	2	960	4	41
13.2.1	9	40	7861	40	3	4	1313	7	47
23.1.2.2	6	19	6008	20	8	22	13542	30	50
23.2	9	19	7967	20	7	26	5446	33	53
13.1.2	12	24	5249	24	1	1	488	2	26
25.2	7	12	1947	13	2	4	1068	6	19
184	5	27	100417	28	4	14	5611	18	46
217	4	5	13991	6	6	23	12519	29	35
216	2	1	170	2	5	22	12349	27	29
143	2	4	4588	5	3	15	7020	18	23

Table 5-9 Statistics of the Top Ten Critical Segments in KY6 (TM metric) with Objective VN10

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Sec. Pipe Elements	Total Sec. Length [ft]	Sec. Isolated Nodes	Total Isolated Nodes
23.1	7	36	13291	36	8	22	13542	30	66
13.2.1	9	40	7861	40	3	4	1313	7	47
23.2	9	19	7967	20	7	26	5446	33	53
25.2	7	12	1947	13	2	4	1068	6	19
184	5	27	10041	28	4	14	5611	18	46
217	4	5	13991	6	6	23	12519	29	35
216	2	1	170	2	5	22	12349	27	29
143	2	4	4588	5	3	15	7020	18	23
140	2	3	741	4	4	19	11608	23	27
13.2.2	8	26	4358	27	1	1	221	2	29

Table 5-10 Statistics of the Top Ten Critical Segments in KY6 (TM metric) with Objective VN5

Seg. ID	N. Valves	Prim. Pipe Elements	Total Prim. Length [ft]	Prim. Isolated Nodes	N. Sec. Iso.	Sec. Pipe Elements	Total Sec. Length [ft]	Sec. Isolated Nodes	Total Isolated Nodes
184	5	29	10053	30	4	16	5623	20	50
217	4	5	13991	6	6	24	12525	30	36
216	2	1	170	2	5	23	12355	28	30
143	2	4	4588	5	3	16	7026	19	24
140	2	3	741	4	4	20	11614	24	28
23.1.2.2.2.2	4	8	3037	9	7	24	12510	31	40
212	2	1	346	2	4	21	11649	25	27
151	2	1	216	2	5	22	11995	27	29
150	2	7	1969	8	3	14	9679	17	25
9	4	9	6739	10	0	0	0	0	10

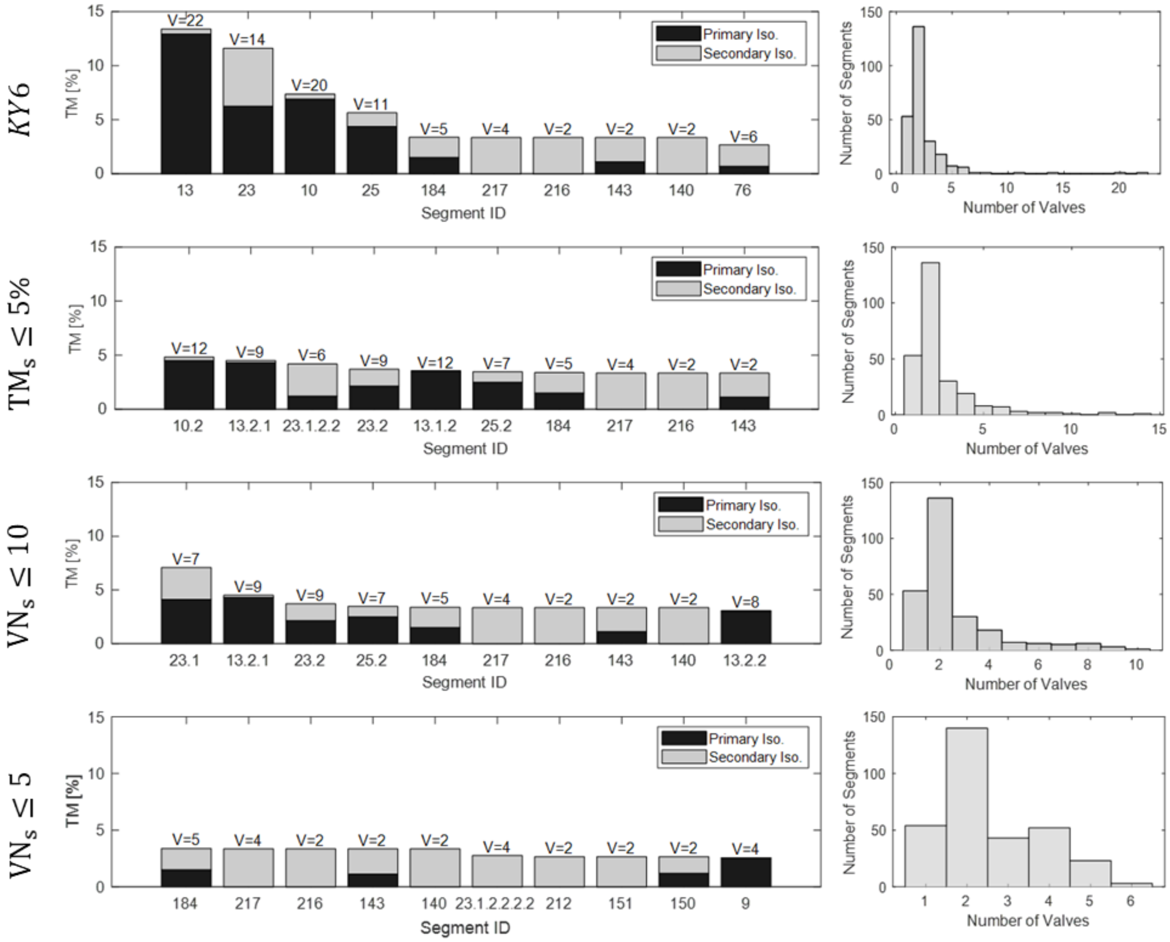

Figure 5-11 (a-d)Top Ten Most Critical Topological Metric Results for KY8, and (e-h) Valve Distribution of KY8 previous to Valve Placement and after Optimization ($\mathrm{TM}_s \leq 5\%, \mathrm{NV}_s \leq 10, \mathrm{NV}_s \leq 5$)

5.8 DISCUSSION of RESULTS

As can be seen in Table 6 and Figure 5-11(a-b), the algorithm is able to reduce the maximum supply loss from 13.38% to 4.83% (i.e. $\mathrm{TM}_s \leq 5\%$) through the addition of 8 new valves. When using the maximum number of valves (i.e. $\mathrm{NV}_s \leq 10$) as an objective, the algorithm is able to reduce the maximum number of valves per segment to 10 while reducing the maximum supply loss from 13.38% to 7.08%, not as much as when using the TM objective but with a similar number of total new valves (i.e. 10). On the other hand, when using a more restrictive objective (i.e. $\mathrm{NV}_s \leq 5$), the algorithm is able to reduce the maximum number of valves per segment to 6 while reducing the maximum supply loss from 13.38% to 3.38% which is superior to the solution obtained using the TM objective, but yet at a much more expensive solution (i.e. requiring 62 new valves). Also of interest is the fact that although segment 10.1.1.1.1 was not listed amongst the top ten segments (i.e. see Figure 5-11(d)) on the basis of its TM score, it did have the maximum valves per segment (i.e. 6) which actually exceeded the maximum target of 5.

This observation raises the question of whether a reduction in demand shortfall could be achieved by simply lowering the maximum number of valves. While this will naturally be the case, this may not lead to the most cost-efficient strategy (i.e. if one uses the number of valves as an implicit measure of the total cost). For example, while a TM value of 4.83% is achieved through the addition of 8 new valves, a value of TM of 3.38% (when using a minimum number of vales, i.e. $\mathrm{NV}_s \leq 5$, as an objective) requires 62 new valves. While not explicitly considered, the fact that the solution associated with $\mathrm{NV}_s \leq 10$ has a TM value of 7.83% and yet requires 10 new valves, would tend to suggest that use of an objective that only focuses on the maximum number of valves will not necessarily produce a globally optimal cost solution.

Further, defining a lower number of valves per segment as an objective generates smaller subdivisions of the existing segments. Consequently, the reduction in the size of the segments leads to a reduction in supply shortfall (i.e. TM). These reductions are linked to the reduction in size of the segment itself (i.e. the number and extent of primary elements in the largest segments), since these segments are reconfigured extensively (e.g. the original segment 13 is partitioned into smaller segments, such as 13.2.2 and 13.2.1 in the $\mathrm{NV}_s \leq 10$ case). Thus, in defining the number of valves per segment as target it is possible to also reduce TM, yet the number of valves required would likely be higher than that expected from only using the demand shortfall as an objective.

Given that this procedure is based on the reconfiguration of existing segments, it is natural to question if the critical segments from the proposed solution for each case can be traced back to the critical segments in the initial condition. Observe that the partitioned segment IDs maintain the label of the parent segment. This means that the first number used as ID will indicate if a segment has remained unchanged (i.e. the same label as the initial segment identification , Segment 184) or if it the new subdivision was previously part of another segment (i.e. Segment 13.1 and Segment 13.2 are the two halves of a reconfiguration of Segment 13). Using this labeling convention, the resulting segments can be traced to the larger original set. Using the results from KY6, the segments that result from the reconfiguration of a critical segment derived from the first analysis of KY6 are bolded in Table 5-7 through Table 5-10. At a glance all the top ten critical segments for both $\mathrm{TM}_s \leq 5\%$ (Table 5-8) and $\mathrm{NV}_s \leq 10$ (Table 5-9), are a subdivision of a critical segment of the initial KY6 layout (e.g. 10.2,13.2.1,23.2) or are a recurring critical segment that has not been altered (e.g. 143,184,216,217). In the case of $\mathrm{NV}_s \leq 5$ a handful of segments are new to the list (e.g. 9, 150, 151, 212), but most segments are linked to one of the initial critical segments (Table 5-7). For all three cases considered, the reconfiguration of the segments has focused on the most critical segments which also happen to correspond to those segments with the highest number of valves. This can be easily observed for segment 13, 23 and 10 which require the use of 22, 14 and 20 valves to effectively isolate those section. However, an assumption that the critical segments will always be those with a high number of isolation valves might not be always valid. Thus, it can be seen that once these segments with high impact (as measured by the TM value) and a large number of valves are reconfigured, the remaining segments of the network have much fewer valves (i.e. 2 to 4) and already have lower impacts, with six of them already below the $\mathrm{TM}_s \leq 5\%$ threshold from the start i.e. 184,217,217,143,140,76 (see Figure 5-11(a)).

The effectiveness of the algorithm in shifting the ranking of the individual segments (regardless of the valve placement objective) as a result of the addition of new valves is reflected in the plots of the TM metrics in Figure 5-11(a-d). As can be seen from the figure, those segments associated with the highest TM scores (i.e. 13, 23, 10, 25) have either been displaced from the other lists all together (i.e. 25), or have been significantly partitioned into smaller segments (e.g. 23.1.2.2) with fewer valves (e.g. 23.1.2.2 now has 6 valves). As can be seen in Figure 5-11(e-h), the algorithm also shifts the distribution of valves from segments with larger numbers to segments with fewer isolation valves as the associated TM score is reduced either explicitly through the use of a TM target value (e.g.$\mathrm{TM}_s \leq 5\%$) or implicitly through a limit on the maximum number of valves per segment (i.e. . $\mathrm{NV}_s \leq 5$). Finally, it is interesting to note that the most stringent limit on the number of valves (i.e. $\mathrm{NV}_s \leq 5$) actually yields a TM value (i.e.

3.38%) less than the value (i.e. 4.83%) associated with the limit on the TM value itself (i.e. $\mathrm{TM}_s \leq 5\%$).

These observations raise the question of whether one of the objectives should be preferred over the other. Particularly in light of the results for the solutions for $\mathrm{TM}_s \leq 5\%$ and $\mathrm{NV}_s \leq 10$, which provide a similar number of total valves (i.e. 8 and 10 valves) but result in different values for the topological metric (i.e. 4.83% and 7.08%) and a different number of maximum valves per segment (i.e. 14 and 10). This may be especially noteworthy since there has not been much detail on the number of valves required for each segment closure in previous optimization approaches (Giustolisi and Savic 2010; Giustolisi 2020).

In the proposed approach the designer/operator may decide on which limiting factor to use based on the specific conditions of the system. For instance, if the isolation valves in the system are reliable (i.e. can be found and operated) a valve placement based on demand shortfall may be more economical while leading to the same level of reliability. However, if the operability of the isolation valves is in question, using a target based on the number of isolation valves per segment may be preferred. This can be seen using a simple example involving the top critical segments for the solutions for $\mathrm{TM}_s \leq 5\%$ and $\mathrm{NV}_s \leq 10$, which require 12 and 7 isolation valves respectively (Figure 5-11(b-c)). For example, defining the failure to isolate a segment as the inability to operate at least one of the required valves to effectively remove a network subsection from service and considering the reliability of the isolation valves in both cases to be 90% (i.e. the isolation valves can be successfully operated 90 times out of 100 uses) the likelihood of failing to isolate the critical segment when needed for Segment 10.2 with 12 valves is just over 70% while for Segment 23.1 this likelihood would be just above 50% (AWWA,2008). Because of this increase in likelihood of failure to close a segment, using an objective that reduces the number of valves per segment may be more desirable if the reliability of the isolation valves is low or uncertain. This observation opens up another whole new line of research questions which have not yet been considered in the current research.

As an alternative to selecting one or the other objective, both metrics can also be plotted against each other to form a pareto front from which the trade-off between the maximum number of valves (as an implicit measure of cost and segment reliability) the amount of loss of water supply. However, in this case, two such curves would be developed. One in which the TM values are derived from the maximum valve solutions and one in which the maximum number of valves is derived from the TM solution. As we have seen from Table 5-6 and Figure 5-11, these solutions do not necessarily overlay each other. Thus, by using two curves, a utility can always identify the best of the two solutions depending upon the primary metric of interest: the maximum number of valves or the potential maximum loss of water supply.

5.9 SUMMARY and CONCLUSIONS

The valve placement procedure presented in this paper involves three main components: the segment identification procedure along with the identification of unintended isolations (Chapter 3) the segment-based assessment (Chapter 4), and the valve placement algorithm. The valve placement algorithm presented in this paper uses a series of graph transformations to construct a heuristic for adding additional isolation valves to the network so as to achieve one of two objectives: 1) minimizing of the loss demand shortages as measured by a topologic metric and 2) minimizing the maximum number of isolation valves associated with any individual segment of pipes. The heuristic allows for water utilities to identify and prioritize valve replacement strategies consistent with financial and broader reliability considerations.

Additionally, it is important to note that proposed procedure only requires an existing EPANET file of the system along with the existing locations of the isolation valves. This information, along with the spatial distribution of demands, can now frequently be directly obtained from a utility via a GIS dataset of the system, which thus allows the algorithm to be readily applied to most systems.

The differences in the objectives used highlights an aspect of the valve placement optimization that has received little previous attention, the number of valves required per segment. This may be especially important in those cases where the number of isolation valves required for closure may need to be minimized (e.g. segments which contain critical infrastructure or emergency events that require a rapid response such as a contamination event). The current case study used applied each objective independently, yet this approach can be adapted to include both metrics in the development of a pareto-front, which will allow utility decision makers to weight inherent trade-offs between the two objectives. Thus, while isolation valves are a practical means of improving reliability, a system operator must consider more than just about increasing the total number of valves. The design/improvement of isolation valve layouts is about the specific locations of the valves added and how each segment is eventually delimited. It is not exclusively about the total number of valves, but also about where they are placed and how their placement reduces the potential loss of water supply.

This heuristic method inspired by graph theory concepts can offer improvements to an existing layout by reconfiguring the segments to reduce their individual impact and potential for spill over by reducing the number of isolation valves required. The graph transformations and articulation points inform the location of possible valve improvements, ensuring a split allowing a feasible solution that uses a limited number of valves. The use or cut points has historically been used to identify vulnerabilities, but it has not been tested extensively on water distribution networks or used to guide in the selection of isolation valve placement. Thus, as with other graph theory concepts there is a potential for further applications in the field.

As highlighted previously, the current algorithm can encounter a situation where the algorithm is no longer able to further reduce a segment. This will typically happen when been applied to system which contain a significant number of non-valved pipes in a grid network. Fortunately, such cases are rare in real systems. However, by adding an additional heuristic in which one or more isolation valves are randomly distributed within such grids, the algorithm can be readily restarted. Additional improvements to the heuristic are possible.

The current heuristic implicitly assumes that each valve has the same cost, while valve costs will be related to the diameter of the pipe in which the valve is placed. Subsequent incorporation of an explicit cost function based on pipe diameters, such as proposed by

(Creaco et al. 2010), would not only allow for an additional valve placement objective, but also allow for a way for the algorithm to directly consider cost when choosing which side of the cut node to place a valve.

In terms of computational complexity theory, the problem examined in this paper represents a NP Hard problem, by virtue of the binary set of decision variables (i.e. place a valve in pipe X, DV = 1, or do not place a valve in pipe X, DV = 0) and the large number of possible solutions associated with the problem (i.e. $\sum_{r=0}^{n}[n!/(r!\,(n-r)!])$ where n = the total number of pipes where isolations valves can be placed, and r = the number of isolations valves that are installed in a given solution which ranges from 0 to n. As a result, the problem has been solved using a heuristic.

While standardized heuristics do exist for such problems, most notably, the Branch and Bound algorithm of Land and Doig (2010), most applications are typically restricted to linear problems in which each sub-problem can be solved using linear programming. Unfortunately, the current problem does not yield itself to such a formulation. Theoretically, an alternative strategy could employ genetic programming using binary decision variables, however, the resulting algorithm would still represent a heuristic, and thus would not be able to guarantee a global optimal solution. Even more importantly, without some type of explicit constraints on the solution space, the number of potential solutions would quickly beyond several tens of millions of combinations, even for a modest system with 25 potential valve locations.

As is, the proposed heuristic has shown that a complete enumeration of the solution space is not necessary to identify the most problematic segments of the network, nor to produce solutions that can satisfy the stated objectives. As a result, the final algorithm provides a trade-off in computational completeness and practicality, which should provide a useful tool as applied to real world networks.

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CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

6.1 FINDINGS

The question of reliability in water distribution systems continues to remain a complex matter. Still, there are practical means to achieve a better performance in case of an emergency with one of them being an improved placement of isolation valves. However, historically, isolation valves have received less attention than other elements in this context. This research seeks to highlight practical measures to improve the reliability of water distribution systems, particularly through the use of isolation valves, by proposing a framework to both analyze the existing valve layout and provide a simple improvement strategy. This framework involves through three basic steps: segment identification, segment assessment, and optimal valve placement.

The segment identification procedure detailed in Chapter 3 illustrates that segment identification can be readily achieved through a series of sequential steps that employ node incident matrices and information readily obtainable from computer files associated with commercial network solvers. By employing EPANET and the MATLAB, the resulting methodology is made accessible to a wider user base. The protocol proposed by the author only requires an EPANET input file which includes the current location of the isolation valves. This feature eliminates the need to create fictional pipes or auxiliary elements with the valve locations. By using the actual location of the existing isolation valves as they are in the system, no additional assumptions on their placement are necessary (i.e. placing valves on both ends of all pipes, locating valves halfway, etc.).

Chapter 4 addresses the next component of the dissertation: the segment-based assessment procedure. The proposed assessment method uses a series of segment failures instead of single link isolations and identifies the location of critical segments using performance metrics based on loss of connectivity, reduction in demand satisfaction, and the ability to fulfill fire suppression requirements. This assessment presents side by side connectivity and hydraulic indicators, as well as considering the firefighting requirements of the system. The later feature is unique to this dissertation and has not been previously addressed in the context of segment failures. Water distribution systems are complex systems and these diverse metrics allow us to identify which metric may be most conservative for a particular distribution system. Based on the results of the case study, it appears that the topological metric is sufficient to identify the most critical segments for most steady state loading conditions. At least for the system examined, it did not appear that the added computational burden associated with the pressure dependent normal demand was sufficient to justify it use, given the fact that the results provided little additional guidance over that which was obtained using the topologic metric. Conversely, the two different fire-flow metrics (i.e. PDFD and PDHD) did provide additional insights about system performance under more extended periods (i.e. 2 hours). This was largely due to the fact that the critical segments highlighted by the pressure dependent fire demand metric focused on deficiencies created by a reduction in access to the storage tanks in the system, rather than on the isolations and connectivity issues. Identifying these additional critical segments could be crucial for appropriate emergency planning. Thus, once extenuating conditions are introduced, the use of pressure dependent simulations can pinpoint other shortcomings in the system (e.g. PDFD and PDHD). Because of this, the latter two metrics may be worthwhile, even if it means an increase in the computation time of the assessment. Generalization of this conclusion to other systems will obviously be dependent on additional case studies.

The existing research community is continuing to transition from single pipe reliability assessments to a segment-based approach. Part of this research has explored the development of surrogate-based reliability metrics, including their potential use in optimal valve placement algorithms. The proposed topological metric was found to be very robust in identifying deficient segments, and thus more consistent than generic surrogate measures such as the number of isolation valves per segment or the length of a segment. As a result, its use is to be preferred, especially for steady state conditions. The utility of the pressure dependent metrics was also demonstrated for extended periods fire demand conditions.

Finally, the optimization algorithm presented in Chapter 5 describes a heuristic approach to improve the existing valve layout of an actual distribution system by explicitly exploiting the connectivity relationships inherent in an undirected graph. The iterative framework takes advantage of graph theory concepts (i.e. cut points) to define an improved valve placement scheme that provides gradual upgrades using the minimum amount of new isolation valves at each step. The use of these graph transformations reduces the solution space for new valve placements and ensures the applicability of the approach to much larger networks. Using this method two objective functions were tested on a case study: (1) reduce the experienced service shortfall to a target limit and (2) decrease the number of isolation valves required to isolate individual system subsections (i.e. segments). Although a few researchers have considered the problem of valve optimization in the context of segments, less attention has been given to the number of isolation valves required for each segment closure. In some cases, the consideration of valve failure or valve criticality may in part address the concern of the increasing likelihood of failure to shut down a segment as the number of valves required to be closed increases. However, the most common constraint is typically the total number of valves added to the entire network, without consideration of the number of valves added per segment. In the application of the proposed methodology for the case study the use of a restriction on the number of valves per segments produced results comparable with those based on addressing the reduction of the maximum demand shortfall. However, although, both results show similar scores for the performance metric evaluated, there is a fundamental difference that may be important for future valving strategies- the number of valves required for segment closure is consistently lower than the number of valves required when one only considers the topologic demand metric.

The proposed valve placement algorithm is used to address a computationally challenging NP-Hard problem by decomposing the problem into feasible sub-problems by applying graph theory concepts in a unique and novel way to water distribution networks. The feasibility and utility of the approach for real systems has been demonstrated by applying it to a real water distribution system in Kentucky.

6.2 POTENTIAL LIMITATIONS

Water distribution system models are mathematical representations of the physical infrastructure, they can be used to predict the performance of the network in a variety of issues (e.g. design, operations, planning, water quality, energy, and emergency planning). However, the quality of these predictions hinges on the validity of the underlying model. Calibrating and validating a hydraulic model is an extensive and data intensive project. However, the topological metric and the optimization procedure take advantage of the topologic structure of the network itself and potential valve locations (which can be further refined by the actual water utility). In recent years, this type of topologic data has become increasingly available as most utilities have begun to transfer such data into computer form through the use of now readily available GIS software. In the state of Kentucky, this process has been standardized and facilitated by the Kentucky Infrastructure Authority.

While the proposed valve placement algorithm seems to be relatively robust, at least two cases were identified which could lead to a premature termination of the algorithm. The first case was when a sole block segment contains only one pipe. This situation could be more expected with tree systems in which a single pipe is served on both ends by multiple connecting pipes (and associated isolation valves). Thus, if there are already six connecting pipes (and valves) associated with the single pipe, then it may not be possible to modify the segment through the addition of a new valve in the pipe in order to reduce the maximum number of valves to be under five. As a consequence, this does not really represent a failure of the algorithm, but an identification of an existing valve structure which will not meet the criteria. In response, it could be argued that a new valve should be placed in the single pipe and the rest of the six valves removed, however this additional type of analysis has not been pursued in the current research. However, the current algorithm will at least identify such anomalies.

The other case where the algorithm may terminate prematurely is potentially more problematic. As discussed in Chapter 5, this can also occur if the algorithm encounters a large grid of pipes which contain no valving. However, in this case, a solution has been proposed, by randomly seeing the network with additional valves until a new cut node naturally emerges. At this point, the algorithm can then continue. At present the current algorithm just identifies such cases, however, the future the code can be readily modified to accommodate this problem.

Given the availability of relevant data, the current assessment has only focused on short-term consequences of a segment shutdown. Presently there is no consideration of the repair time, yet the assessment assumes that the shutdown would be experienced for at least two hours under the fire suppression scenario. A more meaningful review incorporating resiliency could be provided if the typical repair times for the analyzed systems were explicitly known.

The question of reliability also incorporated the likelihood of experiencing a failure. An essential assumption of the proposed assessment methodology is that the isolation valves included in the model can be located and operated in response to a pipe or component failure. In practice, valves that cannot be closed would modify the segment distribution, easily increasing the size of the compromised area and the associated impacts. The likelihood of a failure to find or operate a valve has not been explicitly considered in the current research due to the lack of readily available data from vendors or even utilities, thus the potential for segment expansion has not been explored.

As presented, the assessment has only considered the limited consequences of failure (under an assumption that all valves can be readily identified and closed in a reasonable time frame) and not the probability of failure of a segment or the pipes associated with the segment. A natural expansion of the current work would be to consider the likelihood of failure of the pipes, segments, and isolation valves themselves. However, readily available general information on such parameters is generally lacking, partly because the likelihood of pipe failures and the associated isolations valves tends to be unique to the construction, maintenance, and operation practices of each utility.

It is readily recognized that most of these conclusions are dependent upon the results of a single distribution system. While the fact that the system is an actual distribution system provides some credibility to the results and the associated conclusions, additional analyses with other real systems will be needed in order to verify and validate these observations. Given the variability of the topology of such systems, it is conceivable that there may be some system that have characteristics which may create problems for the algorithm (e.g. systems with large grid network with no valves). Because the ultimate robustness of the algorithm has not been verified by formal mathematical proof, but only through the experimental testing of one case study, it remains possible that other computational limitations may exist.

6.3 OPPORTUNITIES for FUTURE WORK

In this research, the question of reliability has been explored by recognizing the role that isolation valves play in a water distribution network while also providing a procedure that can be applied and to adapted to a wide array of systems. Yet, new questions and avenues of investigations have also surfaced. A few of the future research activities that could be built upon this framework include:

1) Investigate more case studies. Most water distribution systems can be classified by their general topological structure as either 1) branched, 2) looped, or 3) grid, or some combination thereof. It is possible that the performance of a particular segmentation, assessment, and optimization framework will be dependent upon such structures. In order to investigate this potential, it would be important to test the algorithm on range of such topologies. Over the last five years, the author has assisted in the assembly of a data base of diverse systems from both Kentucky and around the world. This information has been compiled in a University of Kentucky Water Distribution System Research Database, which should provide a rich data set for exploring this issue.
2) Integrate the likelihood of failure into the segment-based assessment and the optimization protocol. Both the expected failure rate of a segment and the reliability of the isolation valves will affect the prioritization of the critical segment. Once more detailed observations are available for a system and its isolation valves, the probability of failure can be factored into the framework. As a result, additional collaborations with industry are recommended in order to collect and analyze such data.
3) Incorporate the cost of isolation valves. In the current approach the number of valves is used as an approximation to the cost of the isolation valves, yet it would be more accurate to incorporate the cost as a function of the pipe diameter where the valve is installed. This consideration of cost can be done considering the total

cost of the valves as a global objective or modifying the prioritization score used to select the new valve locations to incorporate the cost of each alternative.

4) Incorporate water age/water quality. In case of a segment shutdown the usual pathways the distribution system follows may be altered, since the network acts as a reactor increasing the residence time of the treated water in the line or inadvertently creating new dead ends which could contribute to a decrease in the quality at the tap. As a result, the impacts of valve closure and segment isolations on water quality should be explored.
5) Investigate the use of decentralized measures to fight fires as an alternative for emergencies. The current framework explored the use of isolation valves as a practical means of increasing reliability, yet in case of fire additional measures might be necessary for a comprehensive emergency plan. Ultimately, the ability to fulfill the fire suppression requirements may rely on the optimal distribution of storage tanks in the network. Thus, it might be useful to couple their design and placement with an explicit consideration of segment and valve reliability or compare the use of decentralized measures (e.g. fire cisterns, separate fire suppression networks connected to fire suppression tanks, etc.), against more traditional measures (e.g. using the same water mains to convey both potable water and water for fire suppression purposes).
6) Investigate the use of articulation points in in other hydraulic problems that can be represented as networks (e.g. sewer systems, or industrial piping systems).

APPENDICES

APPENDIX A. SEGMENT-BASED ASSESMENT RESULTS FOR TEST SYSTEMS

This section presents the tabulated results for each of the test networks (KY6, K8, and KY18) .The results summarize the topologic properties of the networks, the overview of the delineated segments and isolation valve layout, and the characteristics of the critical segments identified by the segment-based assessment (TM, PDND,PDFD and PDHD)

Table A-1 Topologic Metrics for KY6

Topologic Metric		Link-Node	Arc-Node
Link Density	q	0.003161	0.009161
Average Node Degree	K	2.260	2.336
Diameter	D	58363.75	
Average Path Length	l	23308.56	
Spectral Radius	λ^{A}_{1}	3.163	5.353
Spectral Gap	$\Delta\lambda^{A}$	0.0931	1.5533
Algebraic Connectivity	λ^{L}_{2}	0.00160	0.01130
Eigengap	Δ^{L}	0.2618	5.1533

Table A-2 Performance Indicators for KY6

Performance Indicator		(ID)	Unit
Total Length	379816.5	(All)	ft
Number of Segments	256		
Average length of segment	1483.7	(All)	ft
Max.Segment Length	25845.9	207	ft
Min.Segment Length	0.2	81	ft
Length/valve ratio	1645.5	(All)	ft/valve
Average number of valves per pipe	0.4	(All)	valve
Total number of valves	346	(All)	valve
Number of external valves	320	(All)	valve
Number of internal valves	26	(All)	valve
Max.Number of valves to be closed by segment	22	13	valve/segment
Min.Number of valves to be closed by segment	1	1	valve/segment
Average number of valves to be closed by segment	2.5	(All)	valve/segment
Total Demand	1138.1	(All)	GPM
Total Customers	8194.3	(All)	customer
Average demand loss/valve	1165.9	(All)	GPM/valve
Max.Demand loss/valve	303.5	AV-415	GPM/valve
Min.Demand loss/valve	0.0	AV-1	GPM/valve
Average customer loss/segment	51	(All)	customer/segment
Max.Customer loss/segment	1097	13	customer/segment
Min.Customer loss/segment	0	0	customer/segment
Average Customer loss/valve	1166	(All)	customer/valve
Max.Customer loss/valve	2185	AV-415	customer/valve
Min.Customer loss/valve	0	AV-1	customer/valve

* For a customer, a household with 2.5 people on average and a daily demand per person of 80 gallons

Table A-3 Performance Metrics Summary for KY6

	TM	PDND	PDFD	PDHD
Avg	0.62% (All)	0.73% (All)	8.86% (All)	24.96% (All)
Max	13.38% (s=13)	13.39% (s=13)	22.89% (s=13)	28.2% (s=131)
Min	0%(s=1)	0%(s=3)	6.93%(s=110)	21.90% (s=186)
StD	1.41%(All)	2.49%(All)	2.49% (All)	0.84% (All)

Table A-4 Performance Metrics Summary for KY6 (Maximum Demand-Half Tank)

	TM	S
Avg	0.68%	
Max	12.47%	49

Table A-5 KY6 Statistics of the Top Ten Critical Segments (TM metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
13	22	111	22080	110	7	13	2418	20	130	225
23	14	55	21264	55	17	54	20535	71	126	205
10	20	61	11603	61	8	8	2205	16	77	232
25	11	36	7032	37	5	11	2060	16	53	232
184	5	27	10041	28	4	14	5611	18	46	222
217	4	5	13991	6	6	23	12519	29	35	228
216	2	1	170	2	5	22	12349	27	29	230
143	2	4	4588	5	3	15	7020	18	23	230
140	2	3	741	4	4	19	11608	23	27	230
76	6	14	2645	15	3	14	2773	17	32	233

Table A-6 KY6 Statistics of the Top Ten Critical Segments (PDND metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
13	22	111	22080	110	7	13	2418	20	130	225
23	14	55	21264	55	17	54	20535	71	126	205
10	20	61	11603	61	8	8	2205	16	77	232
25	11	36	7032	37	5	11	2060	16	53	232
9	4	9	6739	10	0	0	0	0	10	235
194	5	21	20493	22	1	1	845	2	24	230
207	4	20	25846	21	0	0	0	0	21	231
184	5	27	10041	28	4	14	5611	18	46	222
217	4	5	13991	6	6	23	12519	29	35	228
216	2	1	170	2	5	22	12349	27	29	230

Table A-7 KY6 Statistics of the Top Ten Critical Segments (PDFD metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
13	22	111	22080	110	7	13	2418	20	130	225
59	4	8	2072	9	1	1	454	2	11	233
2	2	3	1646	4	1	1	57	2	6	234
60	2	1	4	2	0	0	0	0	2	235
61	2	1	2	2	0	0	0	0	2	235
23	14	55	21264	55	17	54	20535	71	126	205
131	5	11	4312	12	0	0	0	0	12	232
188	3	3	2695	4	4	9	3927	13	17	229
183	2	1	2	2	0	0	0	0	2	235
9	4	9	6739	10	0	0	0	0	10	235

Table A-8 KY6 Statistics of the Top Ten Critical Segments (PDHD metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
131	5	11	4312	12	0	0	0	0	12	232
79	6	15	2565	16	3	9	3184	12	28	226
217	4	5	13991	6	6	23	12519	29	35	228
20	8	14	1777	15	1	1	67	2	17	233
59	4	8	2072	9	1	1	454	2	11	233
154	2	5	1763	6	0	0	0	0	6	230
145	3	5	2171	6	0	0	0	0	6	234
53	4	8	2699	9	0	0	0	0	9	229
18	7	17	3518	18	0	0	0	0	18	235
142	2	8	1682	9	0	0	0	0	9	232

Table A-9 KY6 Statistics for Top Ten Critical Valves

Valve ID	Valve INDEX	TM [%]	Total Primary Length [ft]	Total Secondary Length [ft]	Total Length [ft]	Merged Segments
~AV-415	1621	0.266673	45457.95	2250.414	43207.54	[90,113]
~AV-414	1620	0.249099	43267.54	33748.27	9519.267	[10,13]
~AV-423	1628	0.229769	41963.46	574.987	41388.47	[86,221]
~AV-452	1652	0.228627	46090.33	2363.107	43727.22	[54,219]
~AV-450	1651	0.228627	43888.82	6939.913	36948.91	[71,121]
~AV-422	1627	0.22766	42500.52	937.688	41562.83	[87,242]
~AV-419	1624	0.225639	42983.65	763.269	42220.38	[88,248]
~AV-417	1623	0.224673	42232.38	7810.918	34421.46	[25,242]
~AV-425	1630	0.217028	43216.47	402.144	42814.32	[85,227]
~AV-424	1629	0.215007	42862.32	22127.92	20734.4	[13,85]

Table A-10 Topologic Metrics for KY8

Topologic Metric		Link-Node	Arc-Node
Link Density	q	0.001817	0.009635
Average Node Degree	K	2.416	2.823
Diameter	D	63527.95	
Average Path Length	l	28060.94	
Spectral Radius	λ^{A}_{1}	3.529	4.560
Spectral Gap	$\Delta\lambda^{A}$	0.10474	0.09946
Algebraic Connectivity	λ^{L}_{2}	0.00111	0.01170
Eigengap	Δ^{L}	0.39205	2.31006

Table A-11 Performance Indicators for KY8

Performance Indicator		(ID)	Unit
Total Length	774233.3	(All)	ft
Number of Segments	294		
Average length of segment	2633.4	(All)	ft
Max.Segment Length	32710.2	60	ft
Min.Segment Length	103.9	265	ft
Length/valve ratio	1586.5	(All)	ft/valve
Average number of valves per pipe	0.3	(All)	valve
Total number of valves	488	(All)	valve
Number of external valves	477	(All)	valve
Number of internal valves	11	(All)	valve
Max.Number of valves to be closed by segment	17	26	valve/segment
Min.Number of valves to be closed by segment	1	7	valve/segment
Average number of valves to be closed by segment	1.6	(All)	valve/segment
Total Demand	1711.4	(All)	GPM
Total Customers	12321.9	(All)	customer
Average demand loss/valve	1152.0	(All)	GPM/valve
Max.Demand loss/valve	325.7	AV-691	GPM/valve
Min.Demand loss/valve	29.1	AV-100	GPM/valve
Average customer loss/segment	62	(All)	customer/segment
Max.Customer loss/segment	1531	49	customer/segment
Min.Customer loss/segment	0	6	customer/segment
Average Customer loss/valve	1152	(All)	customer/valve
Max.Customer loss/valve	2345	AV-691	customer/valve
Min.Customer loss/valve	210	AV-100	customer/valve

* For a customer, a household with 2.5 people on average and a daily demand per person of 80 gallons

Table A-12 Performance Metrics Summary for KY8

	TM	PDND	PDFD	PDHD
Avg	0.50% (All)	0.68% (All)	15.24% (All)	18.01% (All)
Max	12.45% (s=49)	12.47% (s=49)	35.70% (s=26)	30.88% (s=40)
Min	0%(s=6)	0%(s=7)	13.47%(s=152)	4.39%(s=46)
StD	1.08%(All)	1.32%(All)	1.93%(All)	1.50%(All)

Table A-13 Performance Metrics Summary for KY8 (Maximum Demand-Half Tank)

	TM	S
Avg	3.3%	
Max	15.6%	13

Table A-14 KY8 Statistics of the Top Ten Critical Segments (TM metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
49	14	46	20400	46	29	186	60696	207	253	716
1	9	37	20697	32	5	55	37432	58	90	764
4	9	33	14602	33	10	82	28816	88	121	749
60	4	82	32710	73	0	0	0	0	73	792
237	2	42	30772	41	0	0	0	0	41	789
142	9	30	7619	29	9	53	19335	62	91	755
2	2	3	1613	4	7	57	31173	61	65	764
55	3	3	1692	4	6	54	29481	57	61	765
9	16	70	18208	70	9	14	4850	23	93	750
17	13	61	16957	54	1	1	984	2	56	773

Table A-15 KY8 Statistics of the Top Ten Critical Segments (PDND metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
49	14	46	20400	46	29	186	60696	207	253	716
5	5	13	1771	14	0	0	0	0	14	790
1	9	37	20697	32	5	55	37432	58	90	764
46	2	2	3988	3	0	0	0	0	3	793
4	9	33	14602	33	10	82	28816	88	121	749
60	4	82	32710	73	0	0	0	0	73	792
35	3	3	2933	4	0	0	0	0	4	793
8	3	5	8165	6	1	7	3690	8	14	790
237	2	42	30772	41	0	0	0	0	41	789
40	4	4	929	5	0	0	0	0	5	793

Table A-16 KY8 Statistics of the Top Ten Critical Segments (PDFD metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
26	17	46	12482	46	2	2	1218	4	50	780
40	4	4	929	5	0	0	0	0	5	793
39	2	3	2312	4	0	0	0	0	4	793
49	14	46	20400	46	29	186	60696	207	253	716
35	3	3	2933	4	0	0	0	0	4	793
8	3	5	8165	6	1	7	3690	8	14	790
6	3	10	11279	11	0	0	0	0	11	788
4	9	33	14602	33	10	82	28816	88	121	749
3	3	10	2020	9	0	0	0	0	9	791
46	2	2	3988	3	0	0	0	0	3	793

Table A-17 KY8 Statistics of the Top Ten Critical Segments (PDHD metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
40	4	4	929	5	0	0	0	0	5	793
39	2	3	2312	4	0	0	0	0	4	793
49	14	46	20400	46	29	186	60696	207	253	716
35	3	3	2933	4	0	0	0	0	4	793
114	5	15	4859	16	1	1	678	2	18	784
19	6	10	2423	11	0	0	0	0	11	791
5	5	13	1771	14	0	0	0	0	14	790
26	17	46	12482	46	2	2	1218	4	50	780
17	13	61	16957	54	1	1	984	2	56	773
33	15	33	9949	34	3	5	1464	8	42	775

Table A-18 KY8 Statistics for Top Ten Critical Valves

Valve ID	Valve INDEX	TM [%]	Total Primary Length [ft]	Total Secondary Length [ft]	Total Length [ft]	Merged Segments
~AV-691	3476	19.1%	133514.8	51571.64	81943.12	[1,237]
~AV-7	3482	18.8%	125551.5	2366.464	123185.1	[38,253]
~AV-564	3380	18.7%	116167	22098.12	94068.89	[73,241]
~AV-662	3453	18.6%	118200.4	18988.3	99212.15	[56,266]
~AV-657	3448	18.5%	120475.7	5260.618	115215.1	[58,59]
~AV-704	3485	18.5%	126641.3	9034.378	117606.9	[35,36]
~AV-703	3484	18.5%	124201.1	6350.809	117850.3	[36,287]
~AV-701	3483	18.5%	124201.1	7500.717	116700.4	[36,37]
~AV-696	3481	18.5%	127589.2	3241.606	124347.6	[39,40]
~AV-695	3480	18.5%	124389.6	7030.647	117359	[36,40]

Table A-19 Topologic Metrics for KY18

Topologic Metric		Link-Node	Arc-Node
Link Density	q	0.003098	0.007424
Average Node Degree	K	2.355	2.547
Diameter	D	97237.95	
Average Path Length	l	23988.27	
Spectral Radius	λ^A_1	3.193	4.596
Spectral Gap	$\Delta\lambda^A$	0.13084	0.42842
Algebraic Connectivity	λ^L_2	0.00149	0.00541
Eigengap	Δ^L	0.15687	2.12416

Table A-20 Performance Indicators for KY18

Performance Indicator		(ID)	Unit
Total Length	571,347.84	(All)	ft
Number of Segments	344		
Average length of segment	1660.9	(All)	ft
Max.Segment Length	66081.9	236	ft
Min.Segment Length	11.2	314	ft
Length/valve ratio	1228.7	(All)	ft/valve
Average number of valves per pipe	0.5	(All)	valve
Total number of valves	465	(All)	valve
Number of external valves	454	(All)	valve
Number of internal valves	11	(All)	valve
Max.Number of valves to be closed by segment	16	58	valve/segment
Min.Number of valves to be closed by segment	1	1	valve/segment
Average number of valves to be closed by segment	1.3	(All)	valve/segment
Total Demand	1664.4	(All)	GPM
Total Customers	11983.4	(All)	customer
Average demand loss/valve	1629.2	(All)	GPM/valve
Max.Demand loss/valve	353.1	AV-403	GPM/valve
Min.Demand loss/valve	10.5	AV-1	GPM/valve
Average customer loss/segment	46	(All)	customer/segment
Max.Customer loss/segment	1275	58	customer/segment
Min.Customer loss/segment	0	1	customer/segment
Average Customer loss/valve	1629	(All)	customer/valve
Max.Customer loss/valve	2542	AV-403	customer/valve
Min.Customer loss/valve	75	AV-1	customer/valve

* For a customer, a household with 2.5 people on average and a daily demand per person of 80 gallons

Table A-21 Performance Metrics Summary for KY18

	TM	PDND	PDFD	PDHD
Avg	0.38% (All)	0.46% (All)	4.80% (All)	17.80% (All)
Max	10.64% (s=58)	10.64% (s=58)	26.35% (s=80)	44.83% (s=80)
Min	0%(s=1)	0%(s=83)	3.74%(s=239)	15.77%(s=159)
StD	0.98%(All)	1.03%(All)	2.60%(All)	2.23%(All)

Table A-22 Performance Metrics Summary for KY18 (Maximum Demand-Half Tank)

	TM	PDND
Avg	0.38% (All)	23.40% (All)
Max	10.54%(s=58)	40.78% (s=80)

Table A-23 KY18 Statistics of the Top Ten Critical Segments (TM metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
58	16	71	27387	71	21	55	14406	76	147	396
225	4	35	21938	33	6	14	3313	20	53	424
146	15	40	11086	39	1	1	291	2	41	443
76	6	13	4172	14	4	31	16841	32	46	448
96	3	4	92	5	0	0	0	0	5	467
68	8	22	7389	22	6	16	2209	22	44	462
106	3	3	61	4	4	6	854	10	14	465
256	8	19	4803	20	12	38	5484	50	70	455
201	3	4	3623	5	0	0	0	0	5	466
12	3	3	690	4	0	0	0	0	4	466

Table A-24 KY18 Statistics of the Top Ten Critical Segments (PDND metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
58	16	71	27387	71	21	55	14406	76	147	396
225	4	35	21938	33	6	14	3313	20	53	424
146	15	40	11086	39	1	1	291	2	41	443
76	6	13	4172	14	4	31	16841	32	46	448
96	3	4	92	5	0	0	0	0	5	467
68	8	22	7389	22	6	16	2209	22	44	462
63	3	5	3437	6	2	17	66860	19	25	459
106	3	3	61	4	4	6	854	10	14	465
256	8	19	4803	20	12	38	5484	50	70	455
201	3	4	3623	5	0	0	0	0	5	466

Table A-25 KY18 Statistics of the Top Ten Critical Segments (PDFD metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
80	3	3	1085	4	0	0	0	0	4	465
66	6	14	4794	15	2	3	1599	5	20	457
72	3	3	89	4	0	0	0	0	4	467
63	3	5	3437	6	2	17	66860	19	25	459
102	5	10	2642	11	1	1	688	2	13	458
218	2	1	282	2	0	0	0	0	2	467
341	2	1	1151	2	0	0	0	0	2	467
58	16	71	27387	71	21	55	14406	76	147	396
90	3	3	100	4	0	0	0	0	4	466
2	1	1	56	2	0	0	0	0	2	467

Table A-26 KY18 Statistics of the Top Ten Critical Segments (PDHD metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
80	3	3	1085	4	0	0	0	0	4	465
66	6	14	4794	15	2	3	1599	5	20	457
102	5	10	2642	11	1	1	688	2	13	458
72	3	3	89	4	0	0	0	0	4	467
341	2	1	1151	2	0	0	0	0	2	467
218	2	1	282	2	0	0	0	0	2	467
63	3	5	3437	6	2	17	66860	19	25	459
114	2	1	209	2	0	0	0	0	2	467
257	3	3	49	4	0	0	0	0	4	466
121	2	3	323	4	0	0	0	0	4	464

Table A-27 KY18 Statistics for Top Ten Critical Valves

Valve ID	Valve INDEX	TM [%]	Total Primary Length [ft]	Total Secondary Length [ft]	Total Length [ft]	Merged Segments
~AV-403	2172	0.21216	64281.71	168.878	64112.84	[95,96]
~AV-165	1907	0.206939	63119.44	1089.487	62029.95	[255,279]
~AV-240	1991	0.204364	65400.72	1372.607	64028.11	[211,213]
~AV-167	1909	0.200538	62963.09	407.097	62555.99	[259,298]
~AV-166	1908	0.200538	62935.23	373.238	62561.99	[258,259]
~AV-244	1995	0.199358	66048.44	1783.148	64265.29	[209,210]
~AV-24	1990	0.198779	64544.79	7649.399	56895.39	[68,212]
~AV-243	1994	0.197011	65554	1398.267	64155.73	[209,313]
~AV-239	1989	0.196193	60403.97	2148.626	58255.35	[213,234]
~AV-242	1993	0.195288	64988.92	809.189	64179.73	[197,336]

APPENDIX B. TEST SYSTEM SCHEMATICS WITH CRITICAL SEGMENTS

This section presents the network plots for each of the test networks (KY6, K8, and KY18) .In additions to the plot representing the elements of the network, each test system is presented in a Link-Node topology and an Arc-Node topology with the critical highlighting the critical segments for each metric (TM, PDND,PDFD and PDHD)

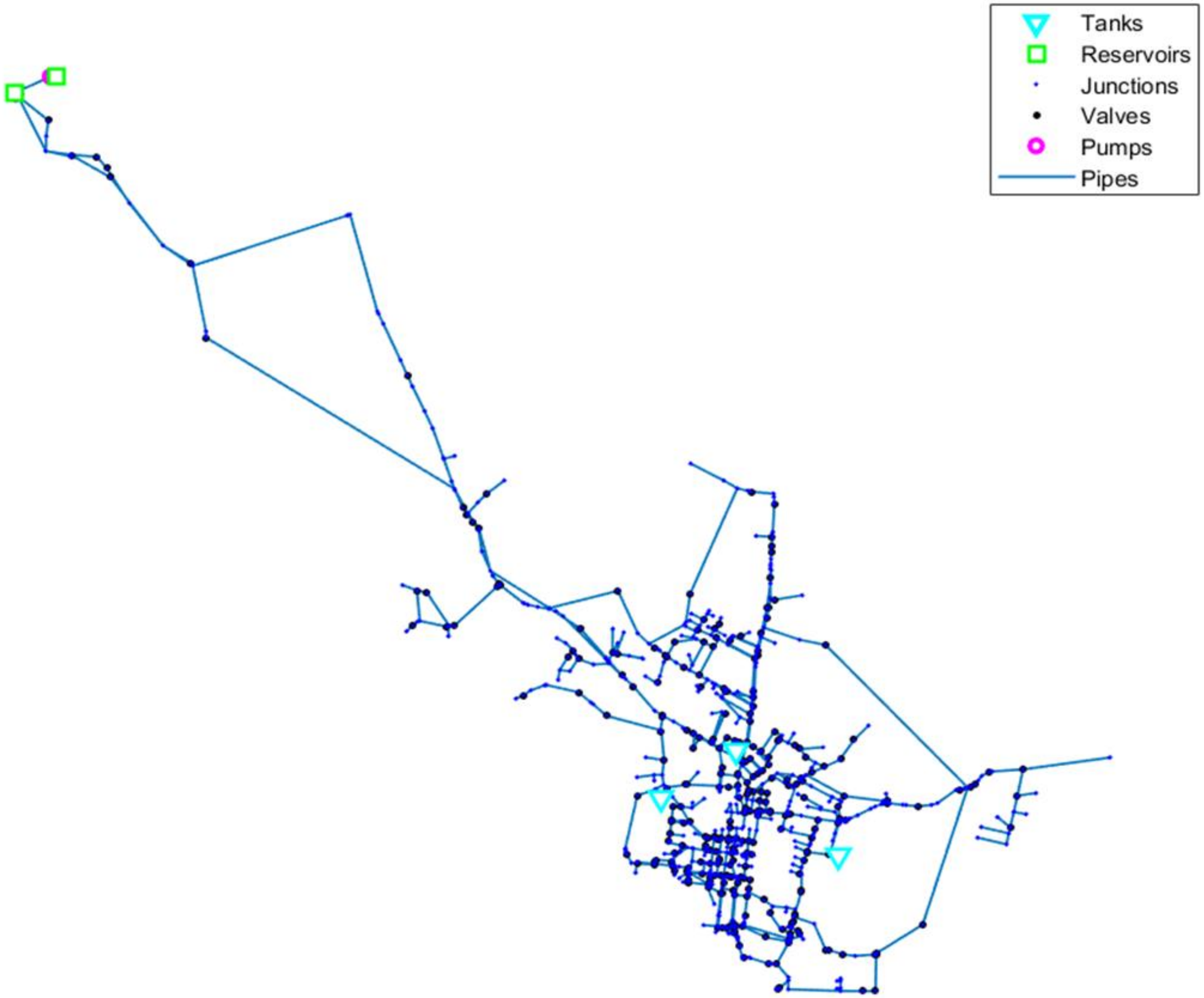

Figure B-1 KY6 System Schematic

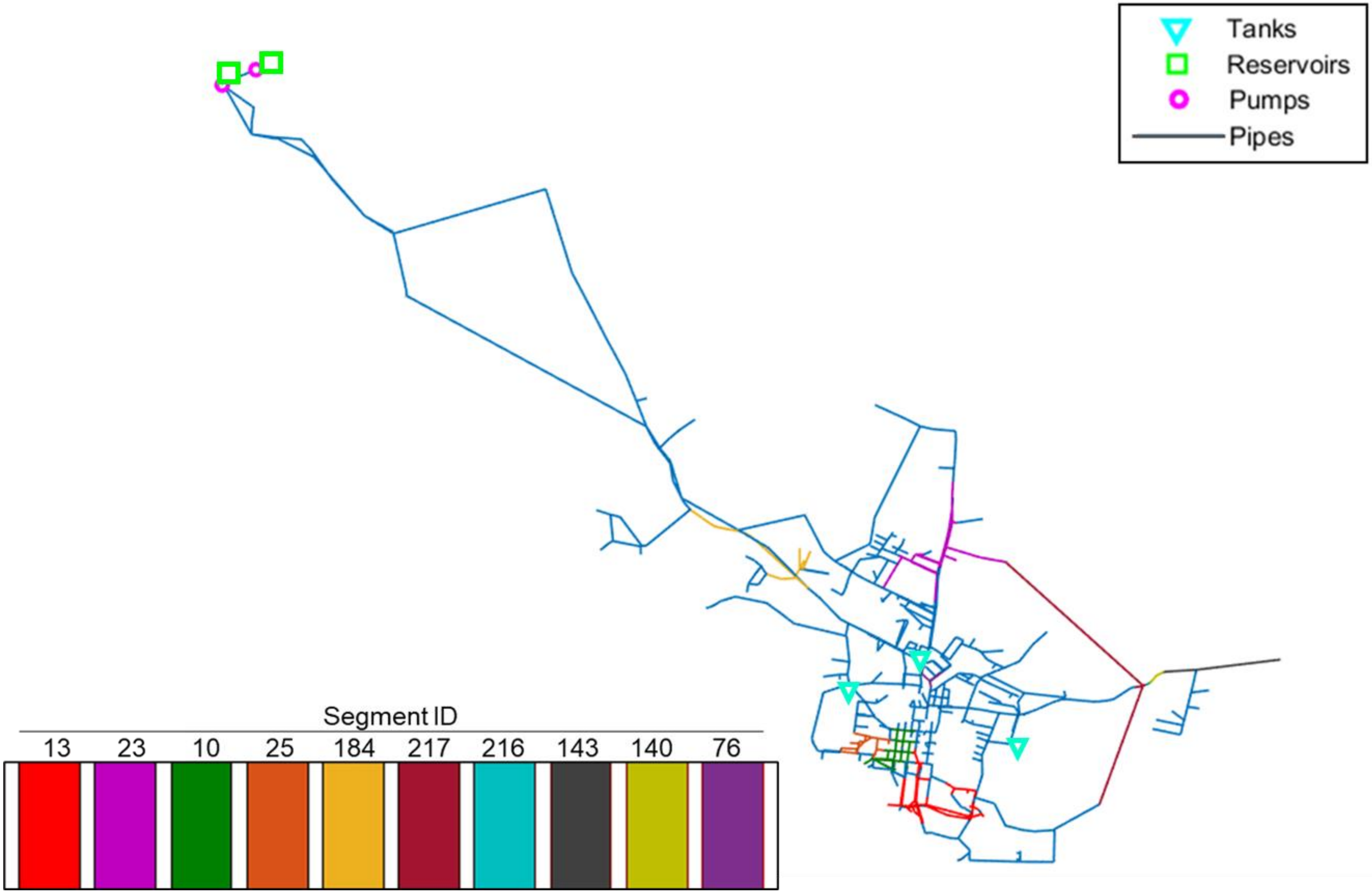

Figure B-2 KY6 with highlighted critical segments (TM)

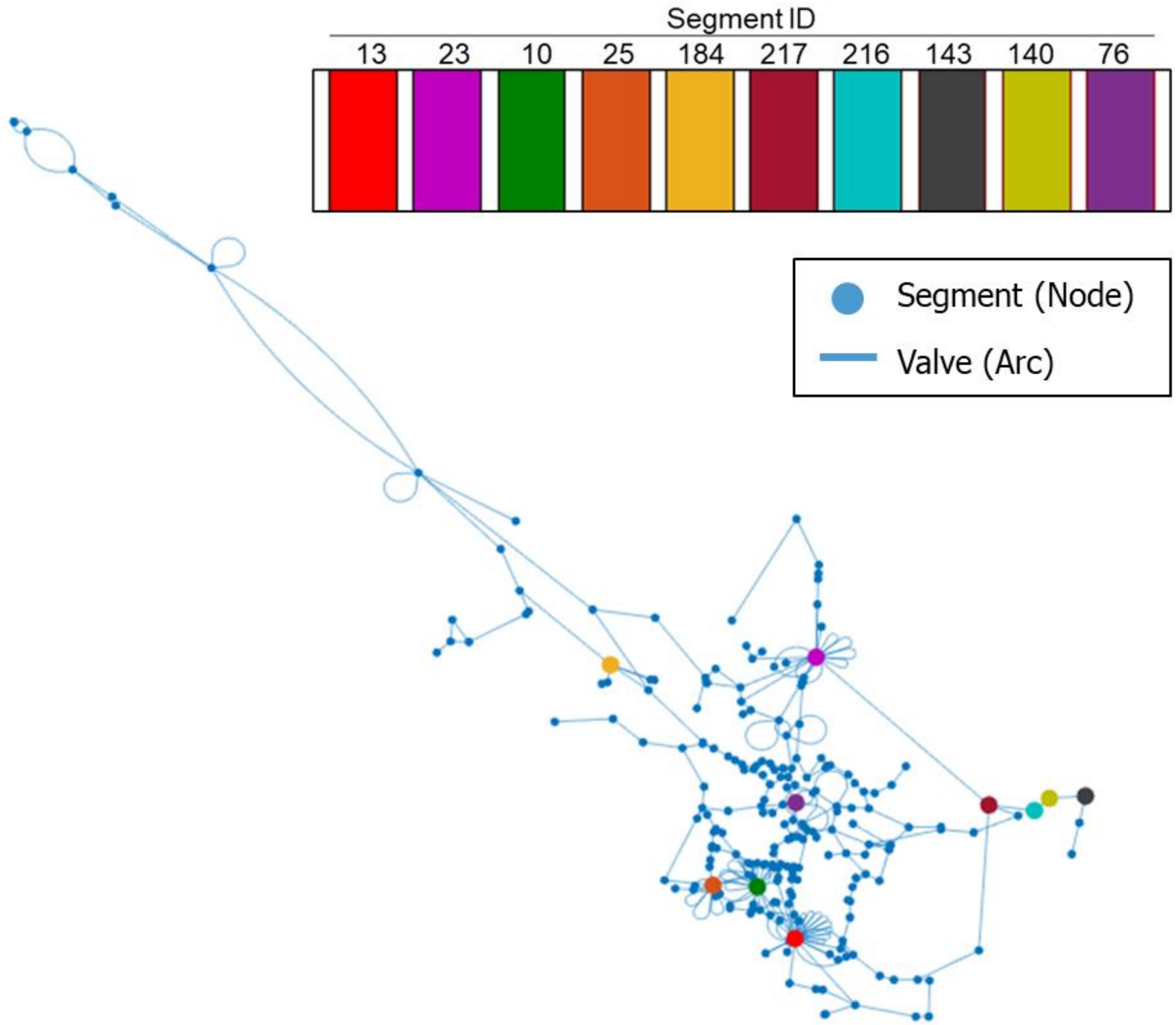

Figure B-3 KY6 with highlighted critical segments (TM) with Arc-Node topology

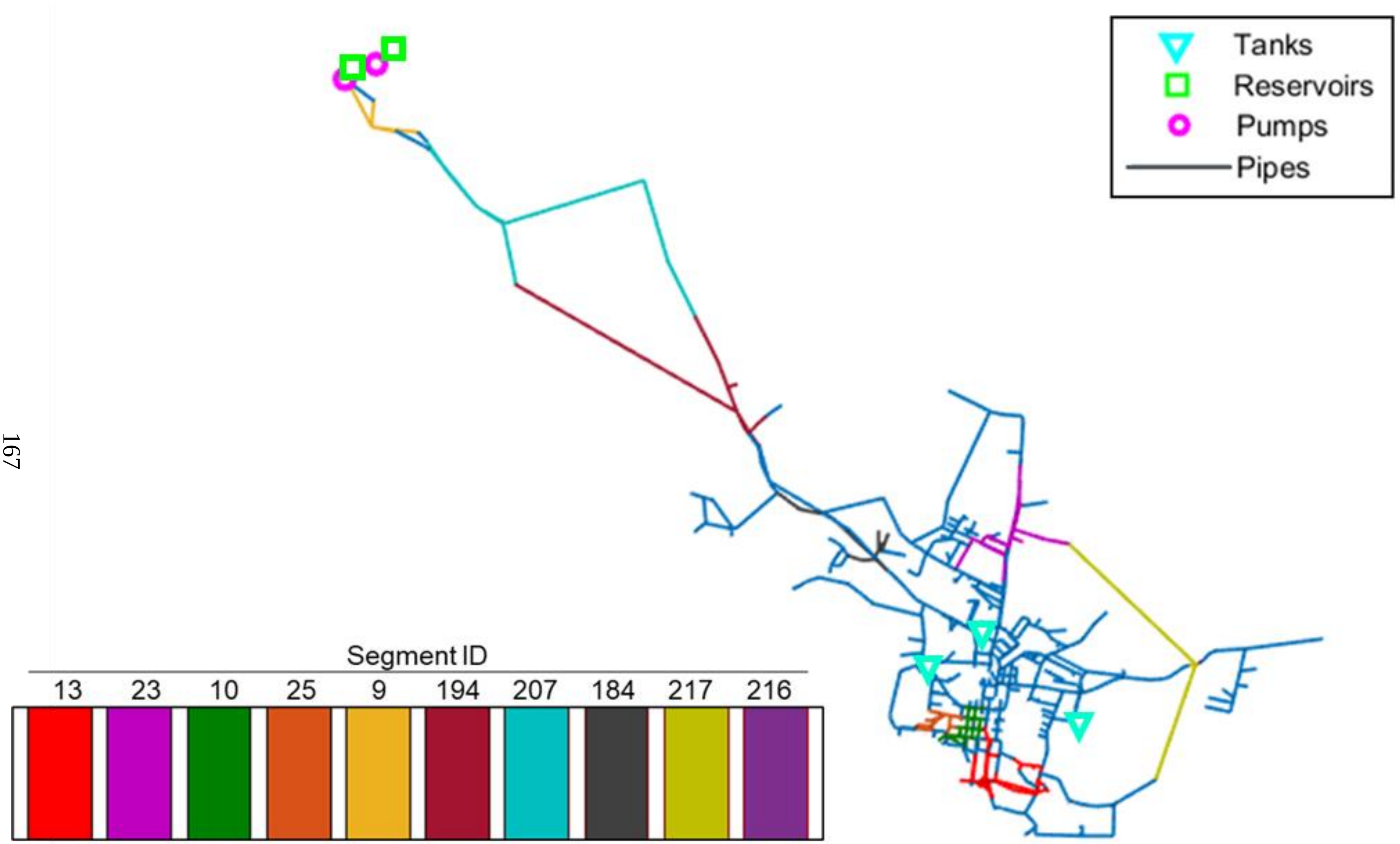

Figure B-4 KY6 with highlighted critical segments (PDND)

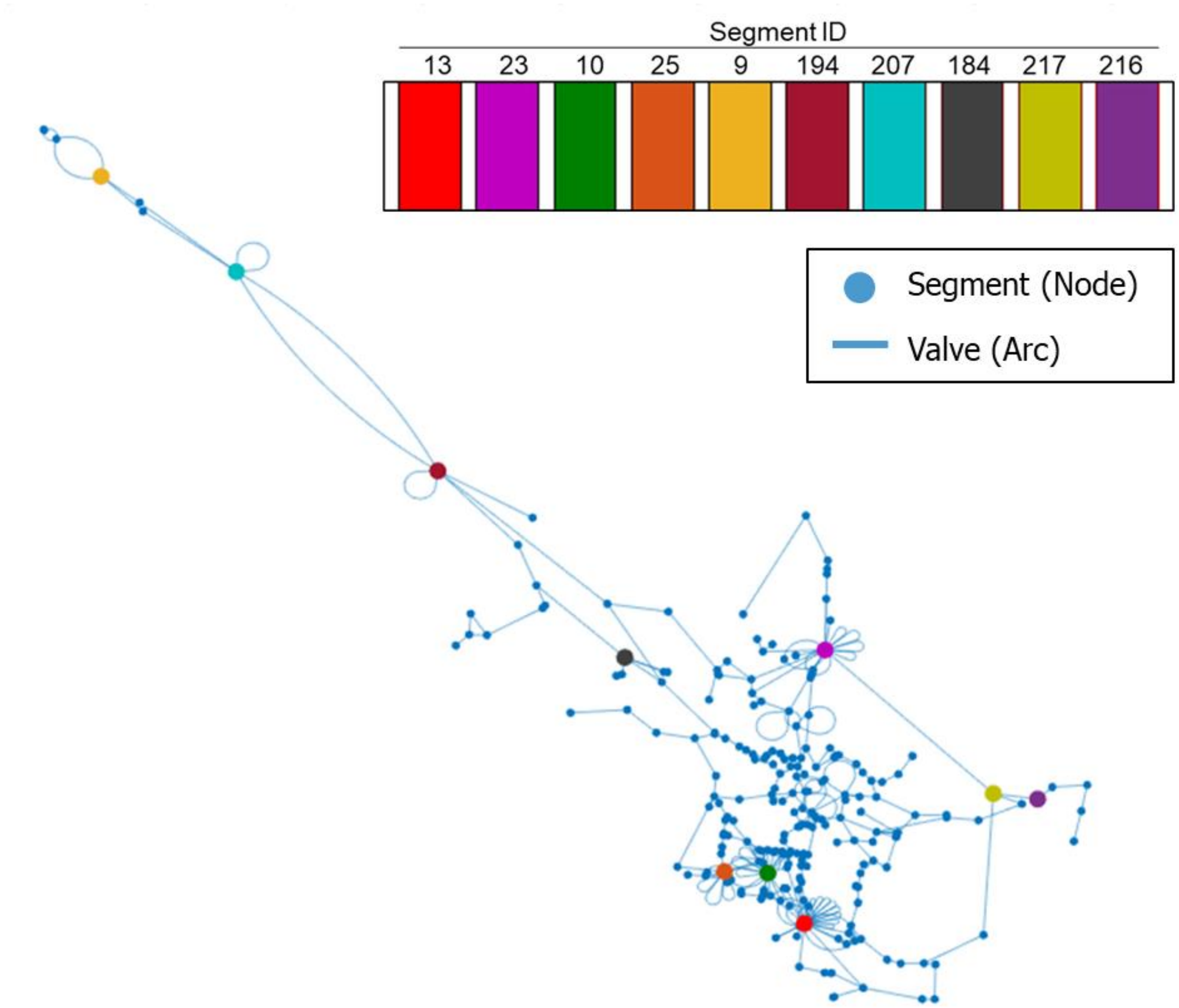

Figure B-5 KY6 with highlighted critical segments (PDND) with Arc-Node topology

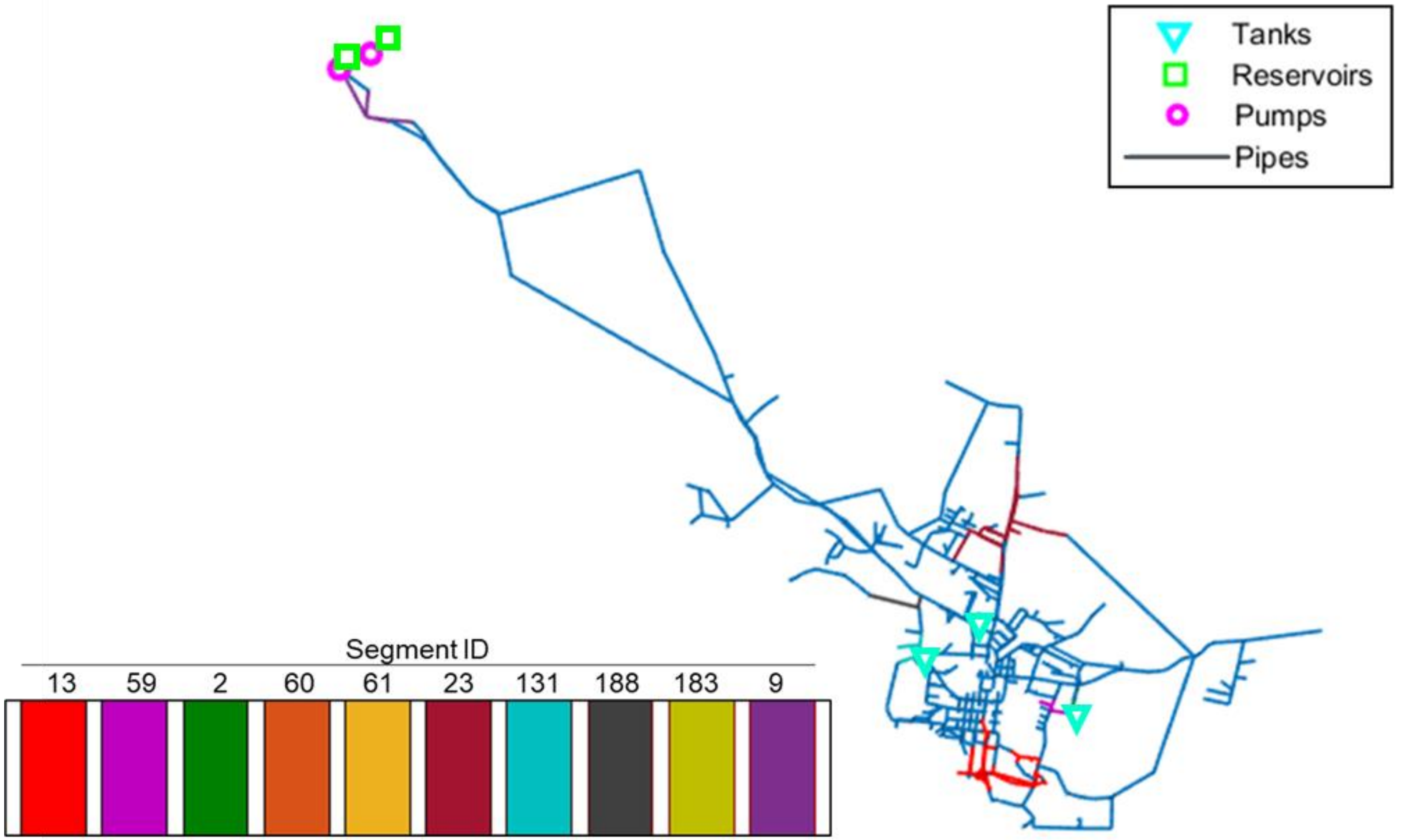

Figure B-6 KY6 with highlighted critical segments (PDFD)

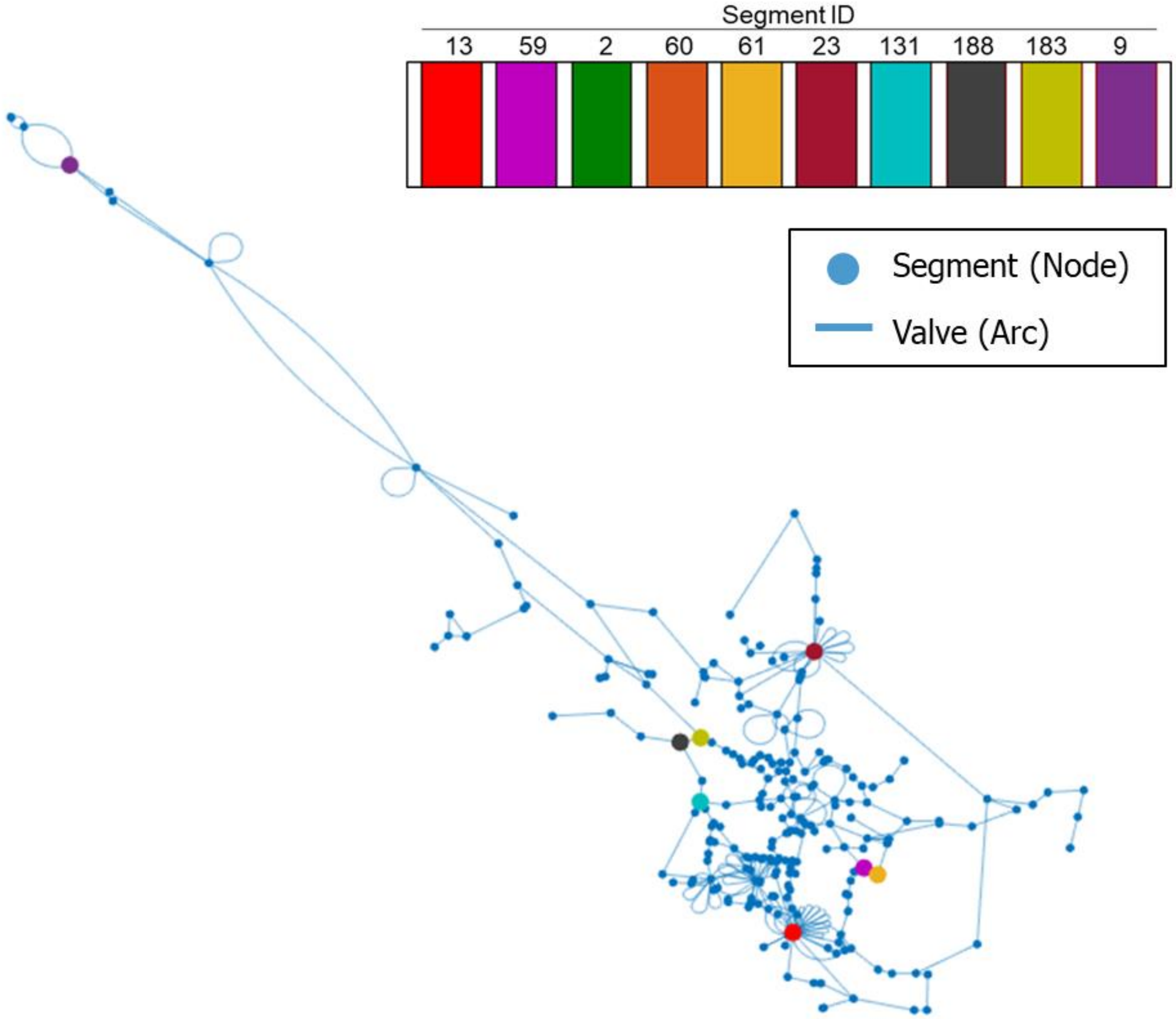

Figure B-7 KY6 with highlighted critical segments (PDFD) with Arc-Node topology

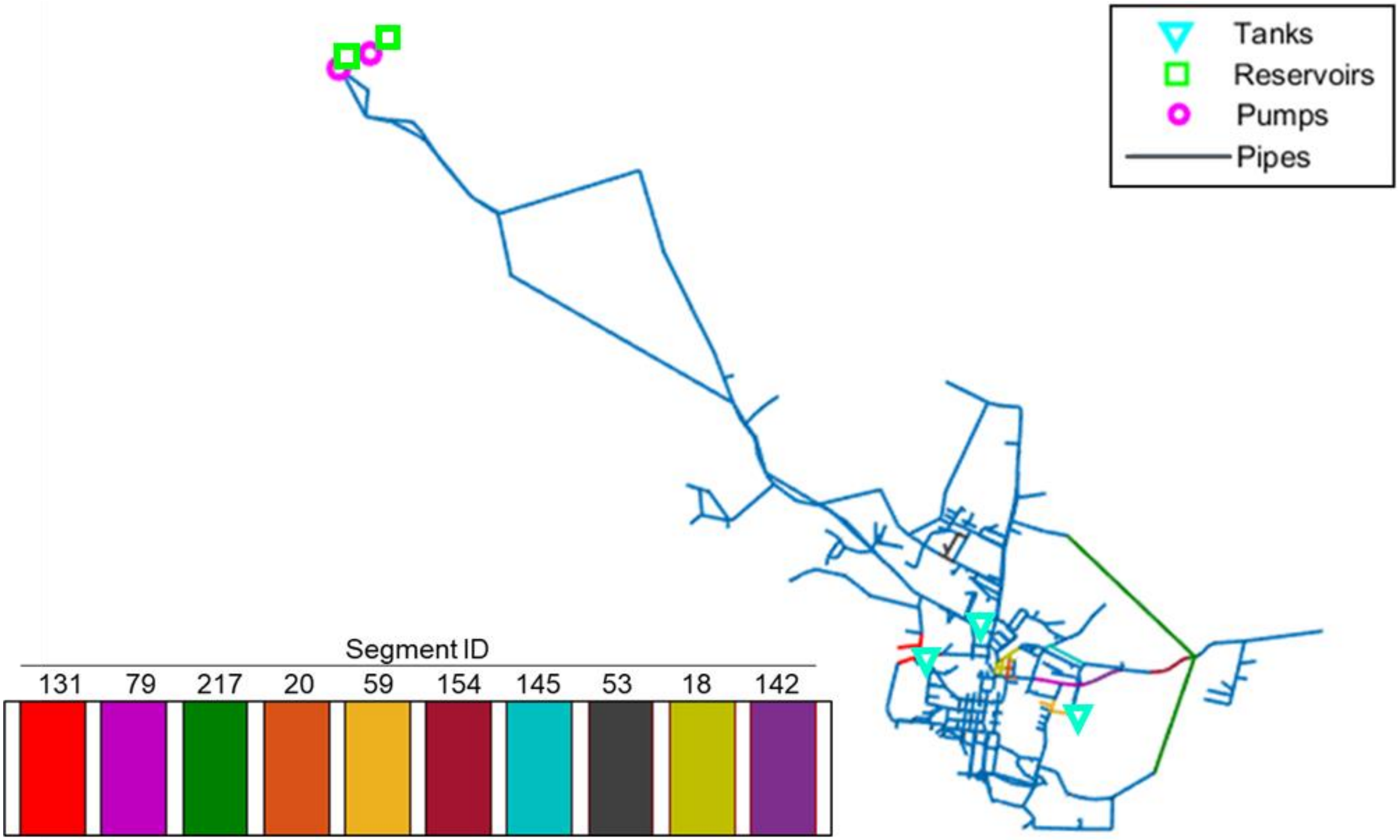

Figure B-8 KY6 with highlighted critical segments (PDHD)

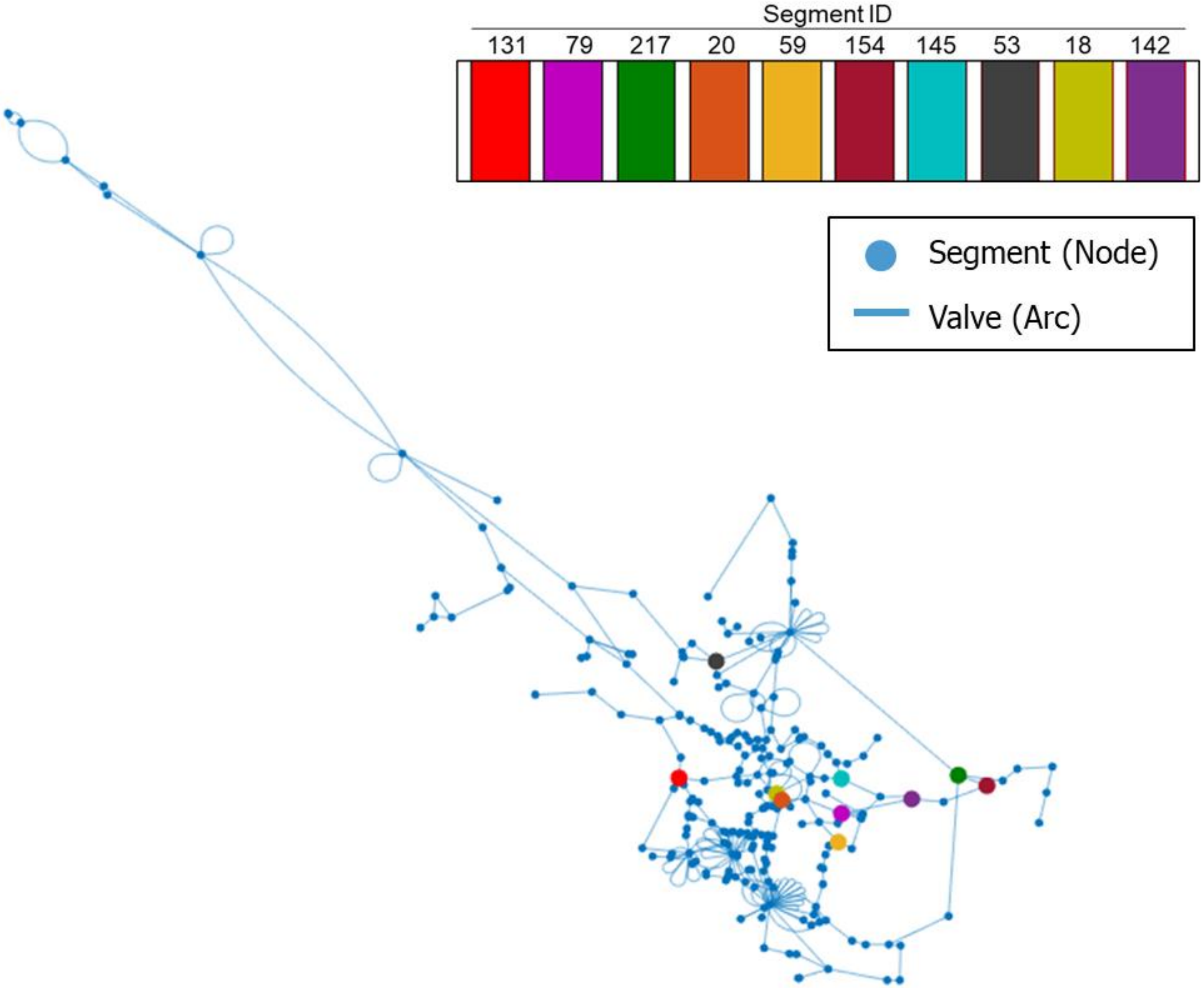

Figure B-9 KY6 with highlighted critical segments (PDHD) with Arc-Node topology

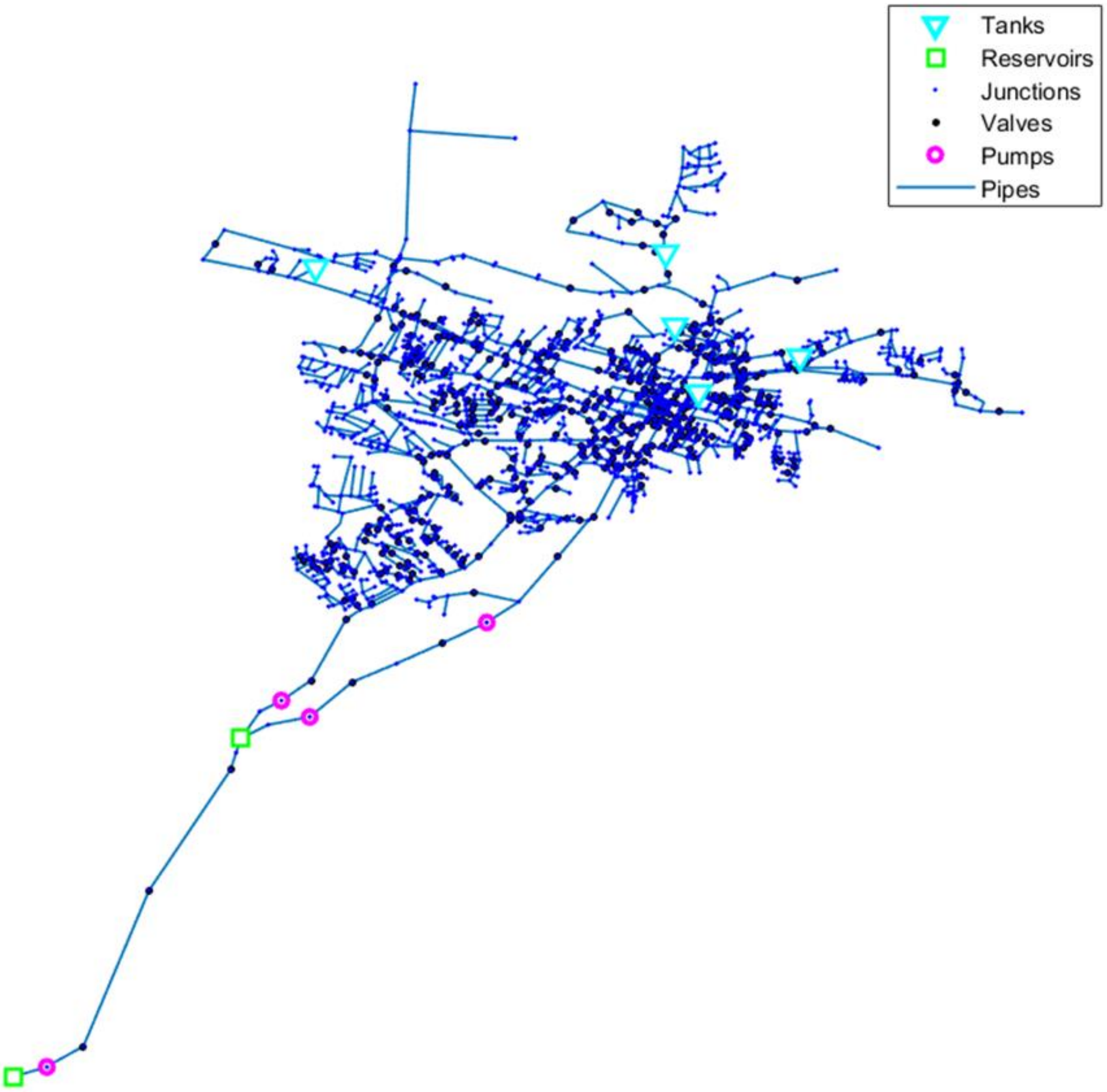

Figure B-10 KY8 System Schematic

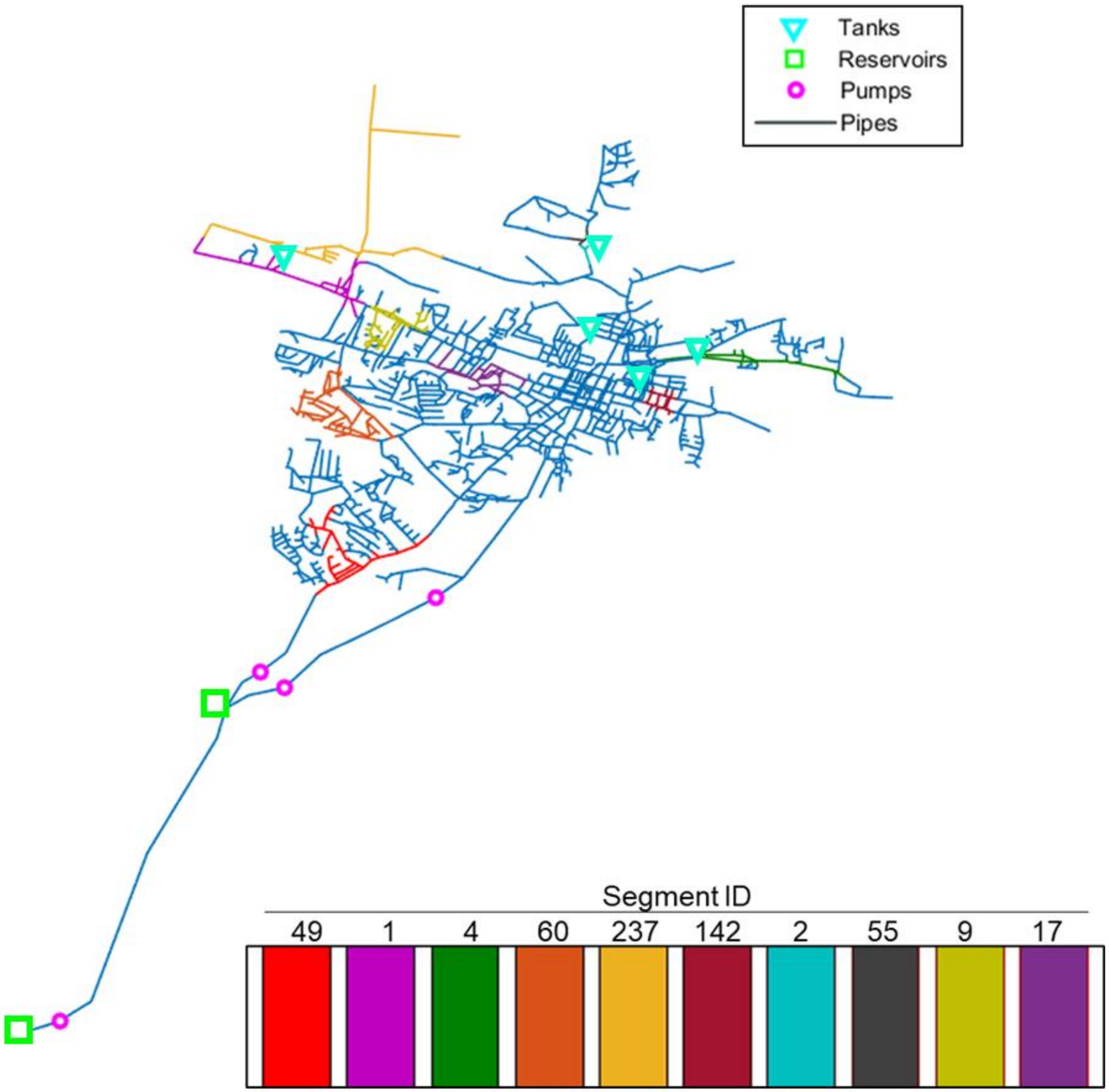

Figure B-11 KY8 with highlighted critical segments (TM)

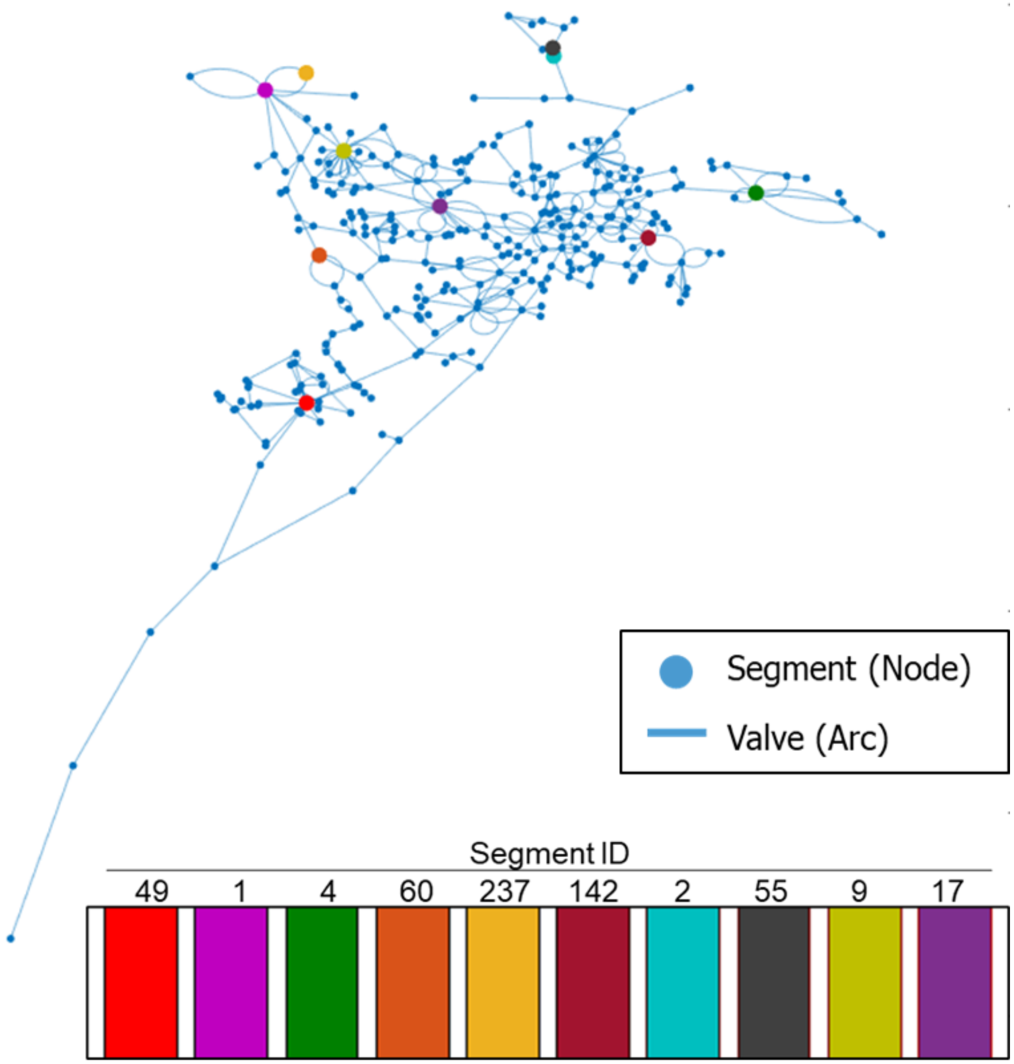

Figure B-12 KY8 with highlighted critical segments (TM) with Arc-Node topology

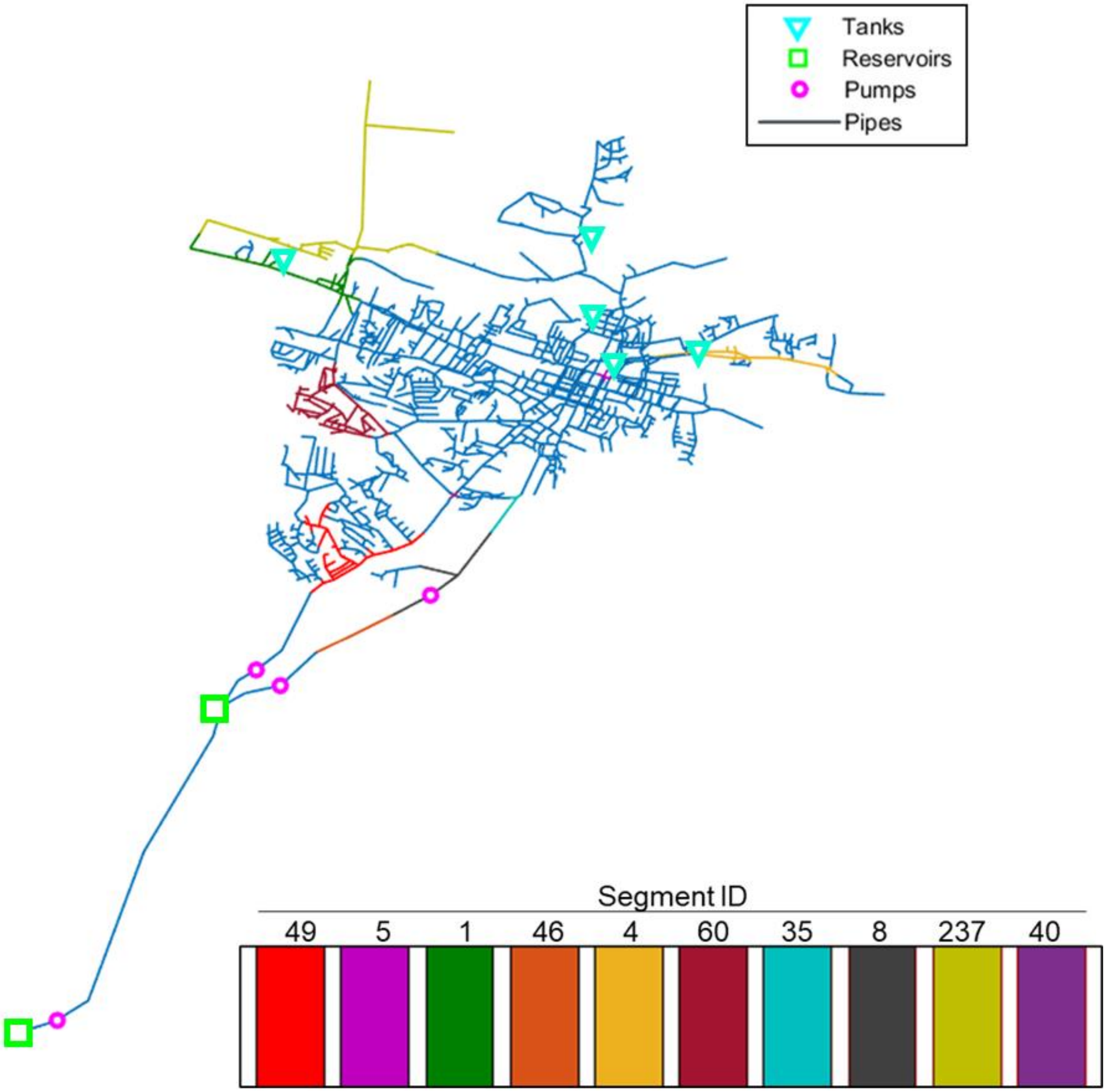

Figure B-13 KY8 with highlighted critical segments (PDND)

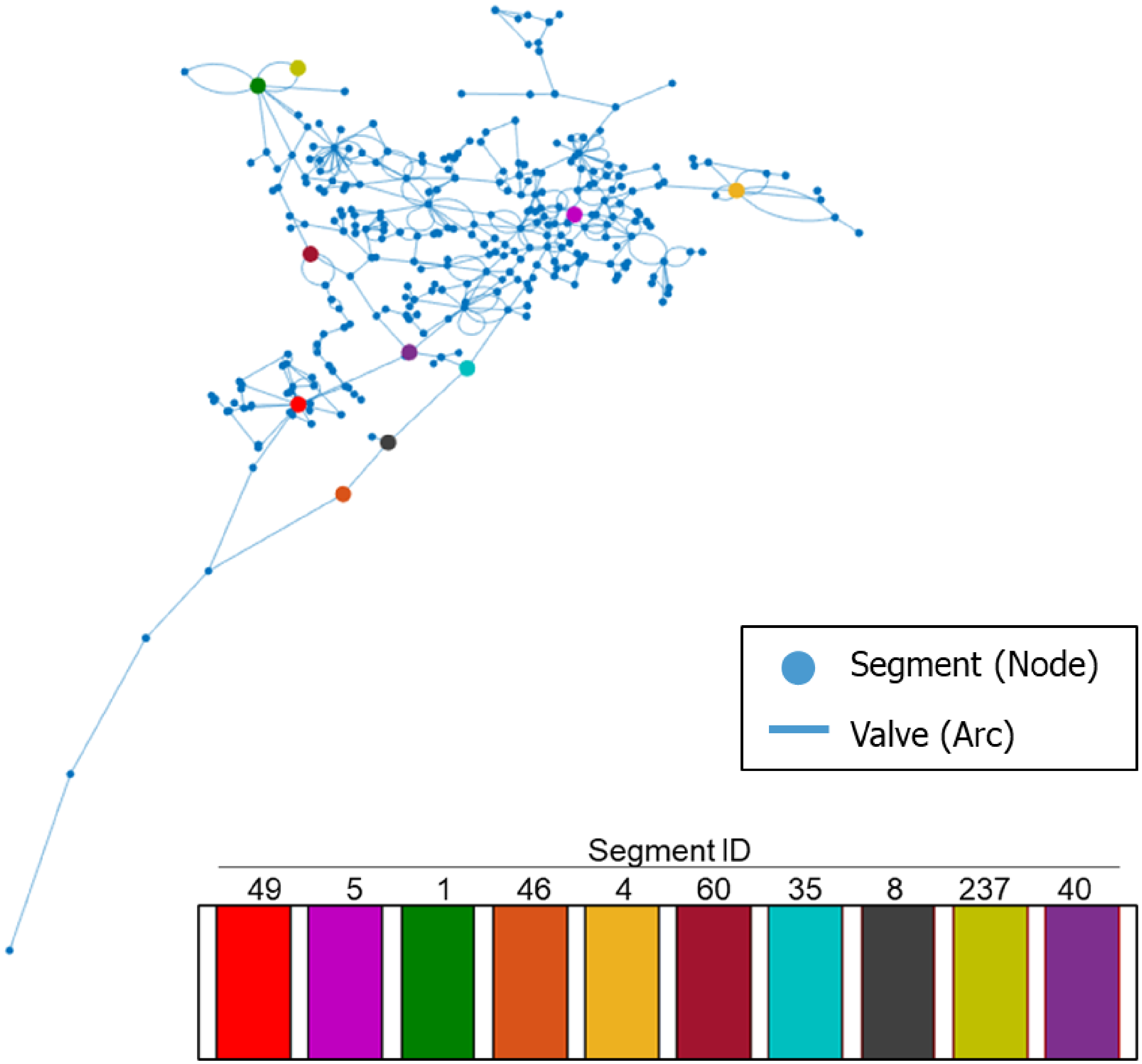

Figure B-14 KY8 with highlighted critical segments (PDND) with Arc-Node topology

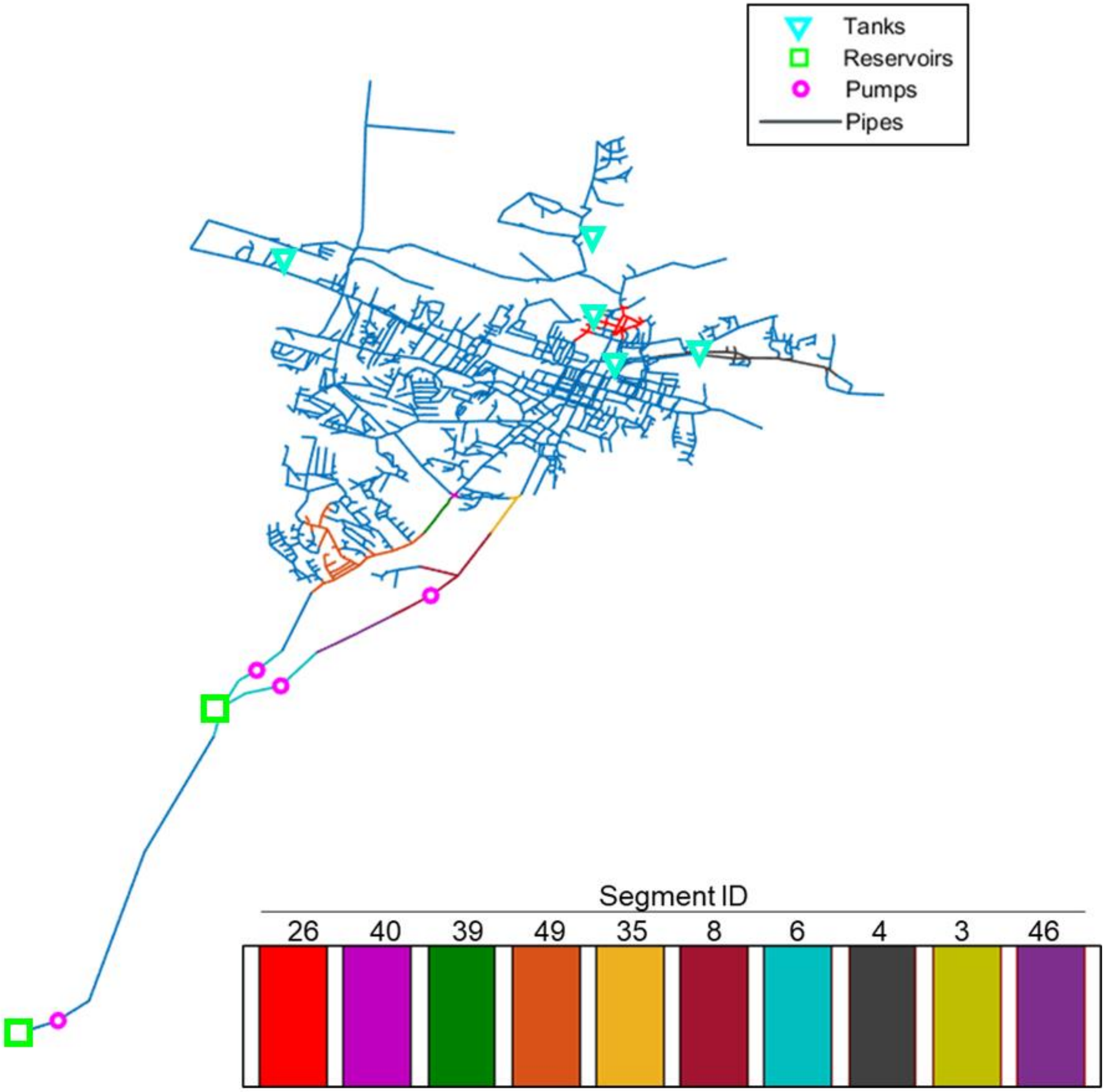

Figure B-15 KY8 with highlighted critical segments (PDFD)

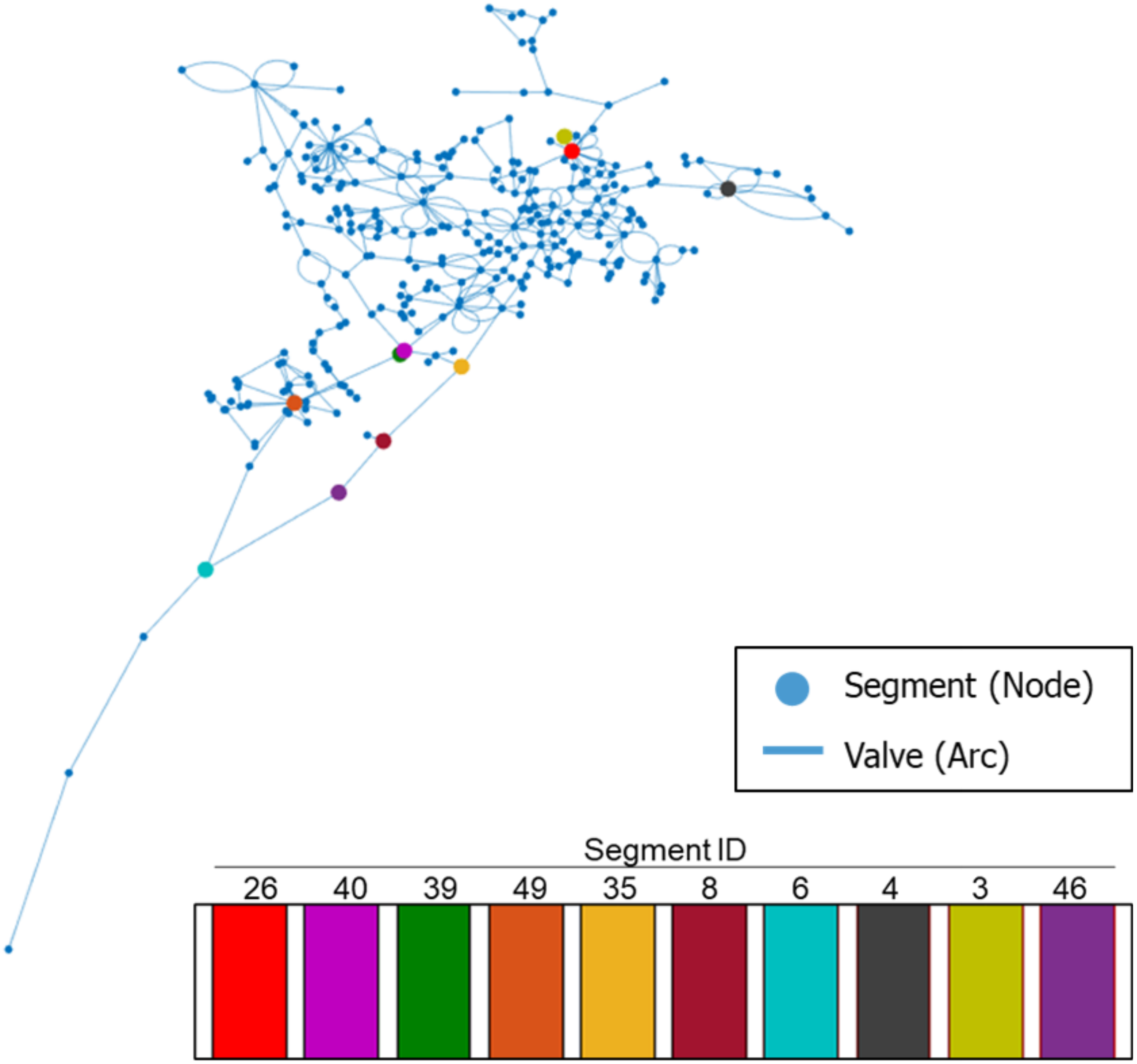

Figure B-16 KY8 with highlighted critical segments (PDFD) with Arc-Node topology

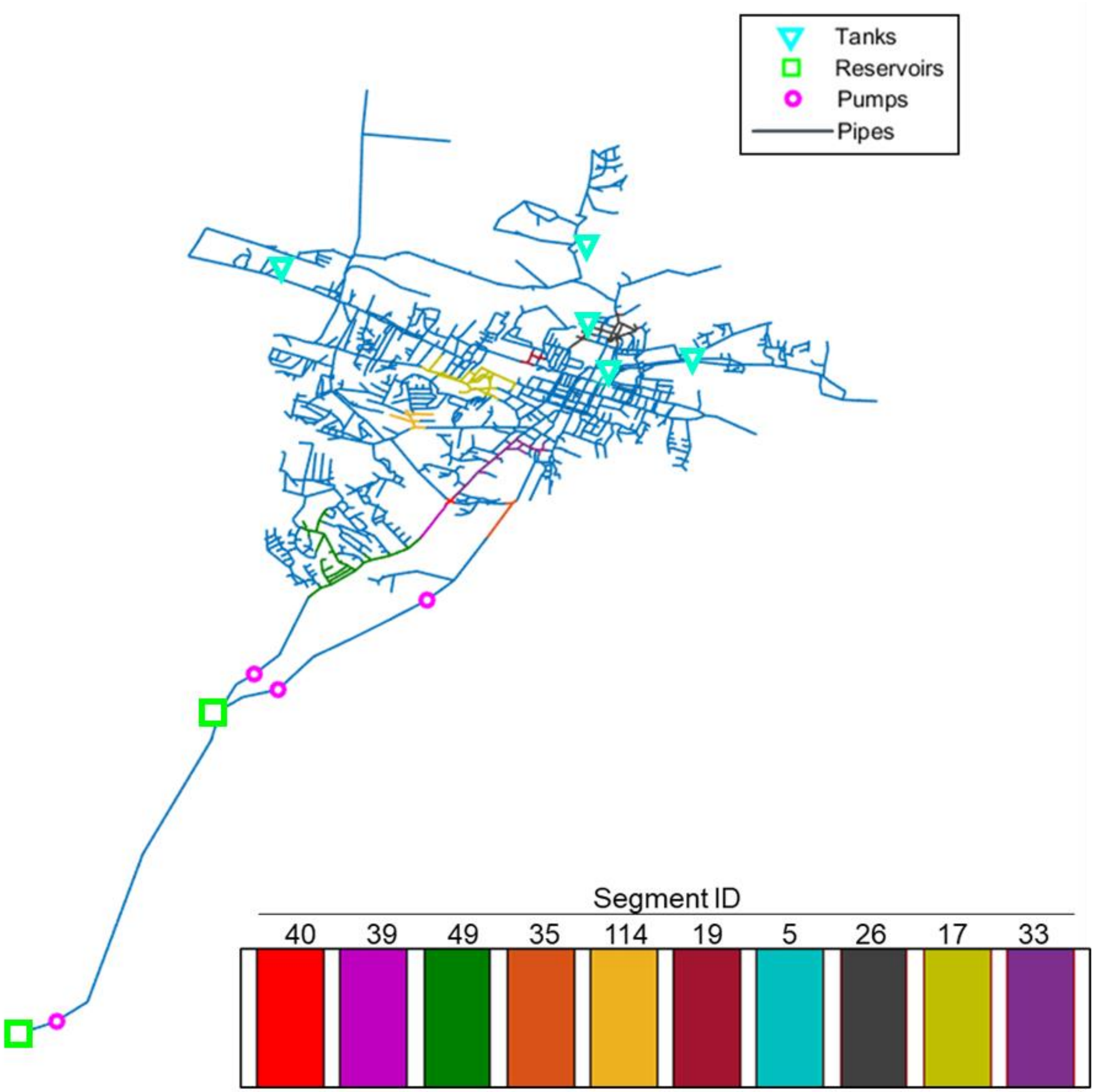

Figure B-17 KY8 with highlighted critical segments (PDHD)

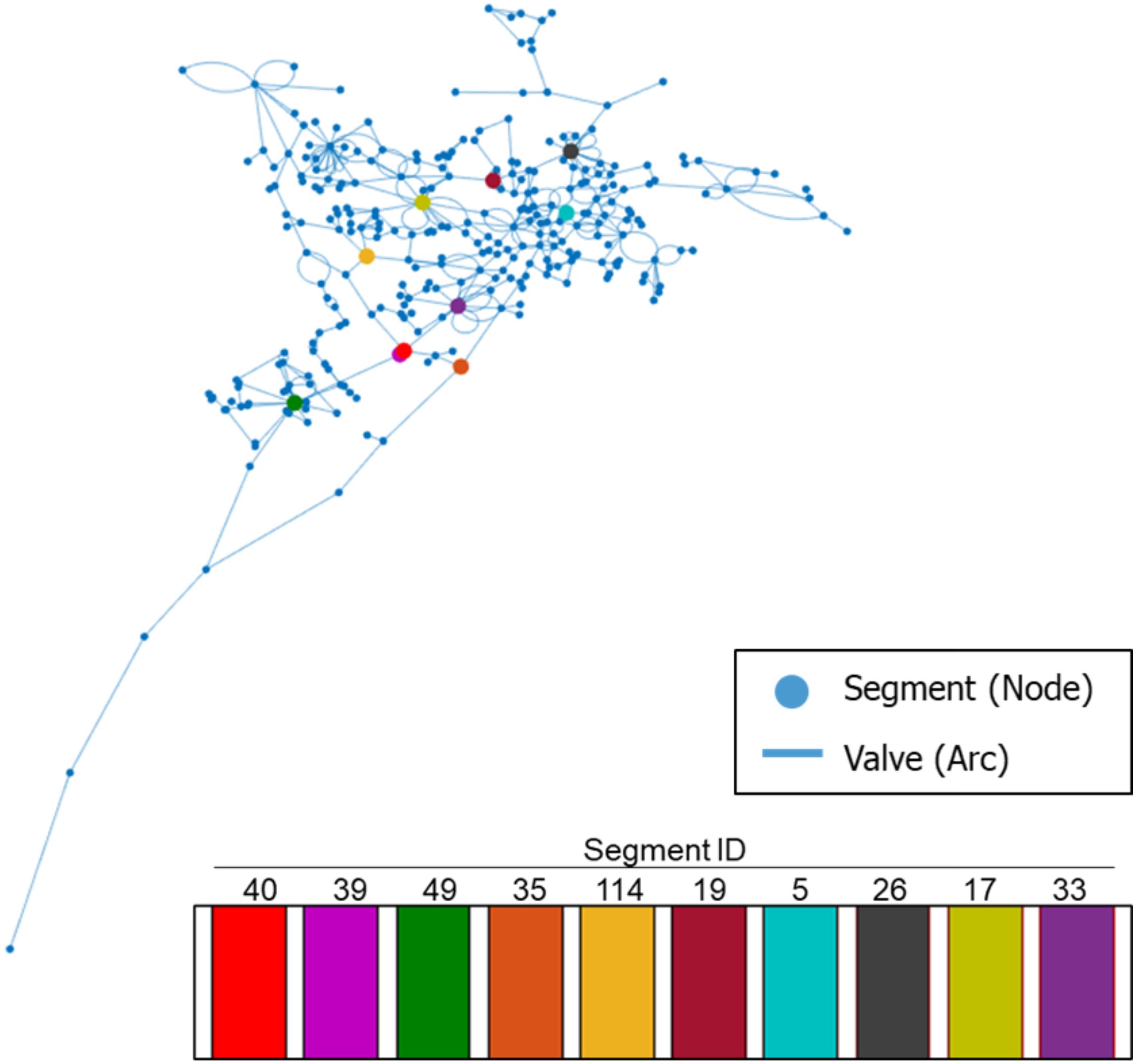

Figure B-18 KY8 with highlighted critical segments (PDHD) with Arc-Node topology

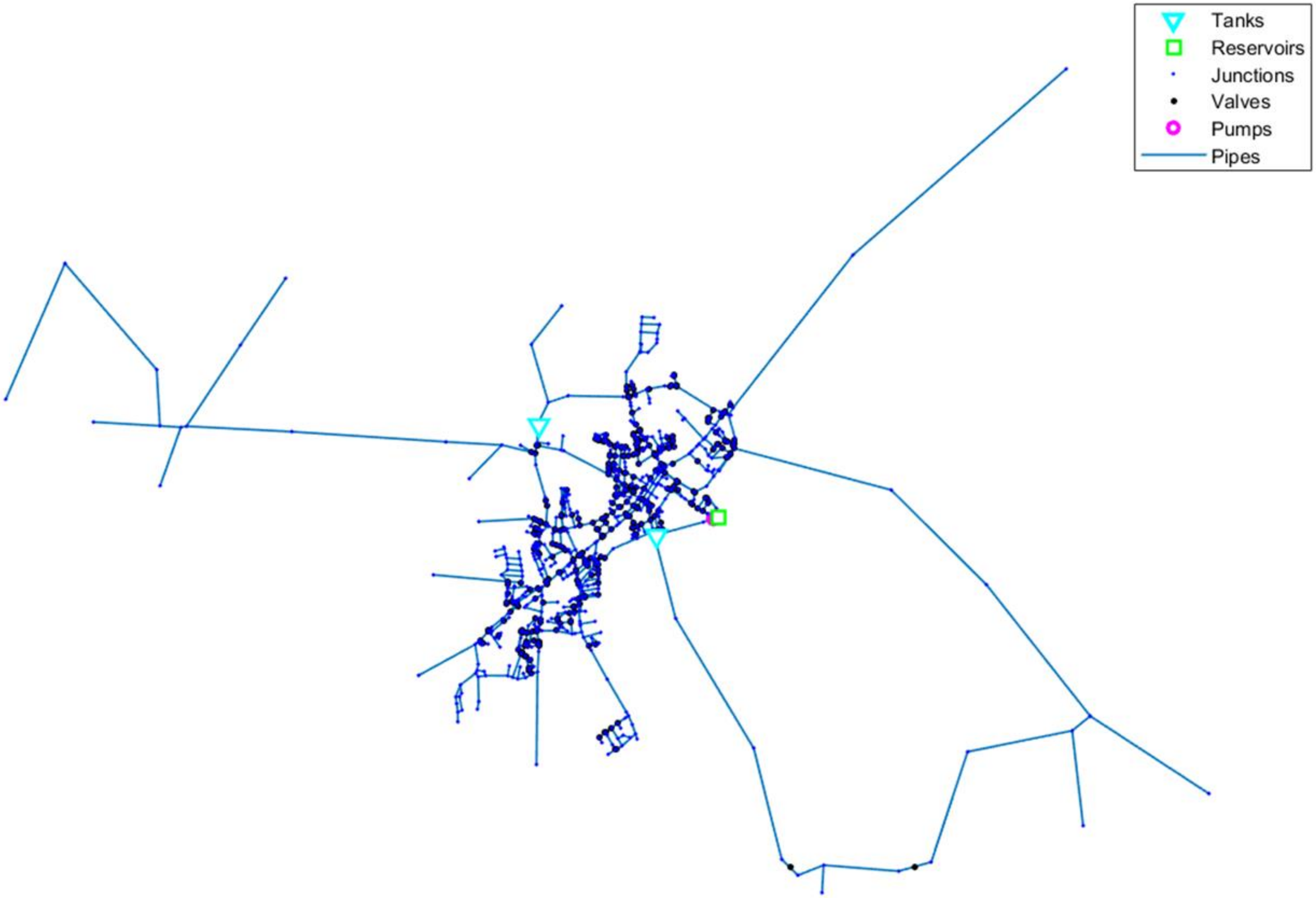

Figure B-19 KY18 System Schematic

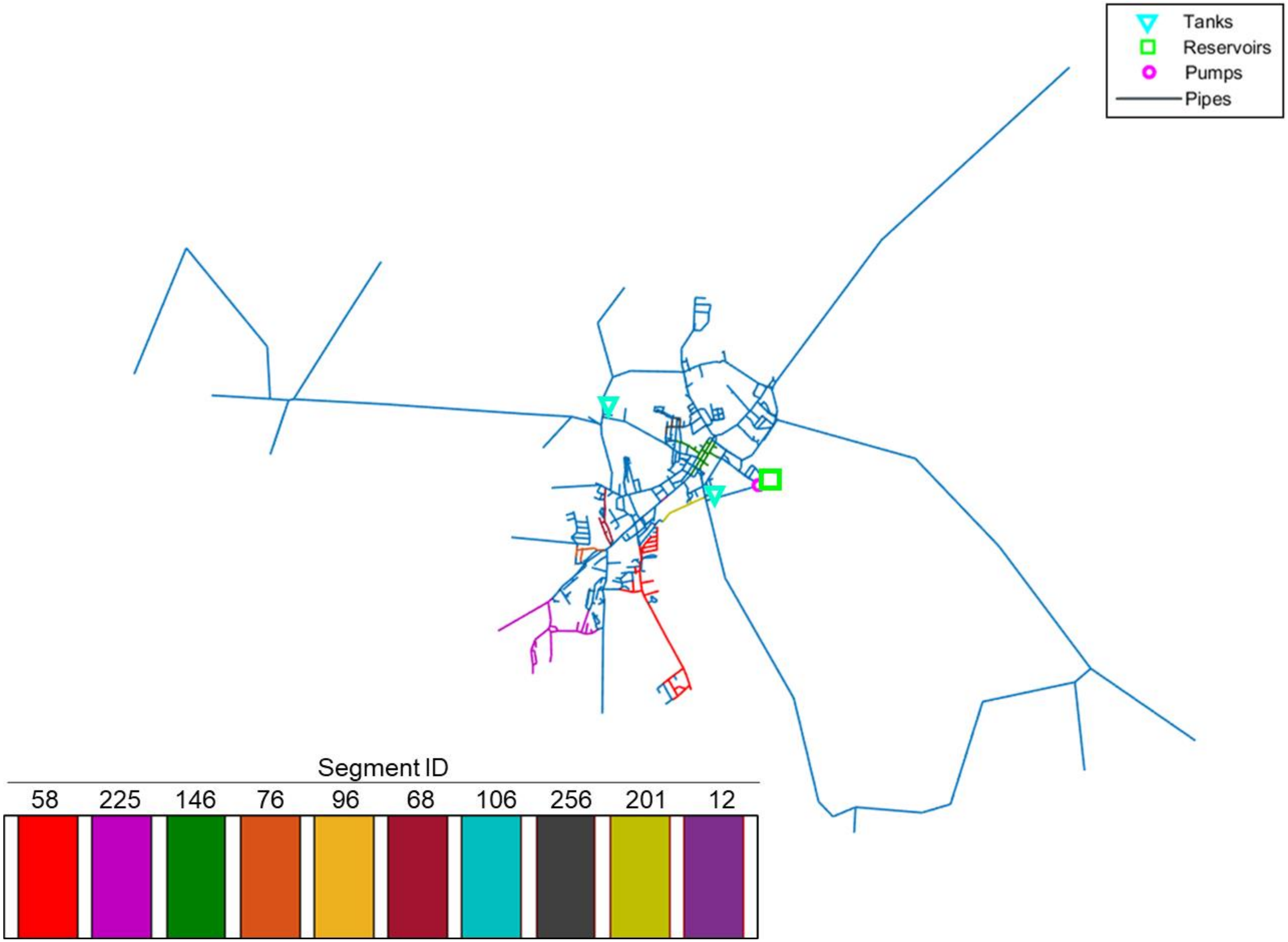

Figure B-20 KY18 with highlighted critical segments (TM)

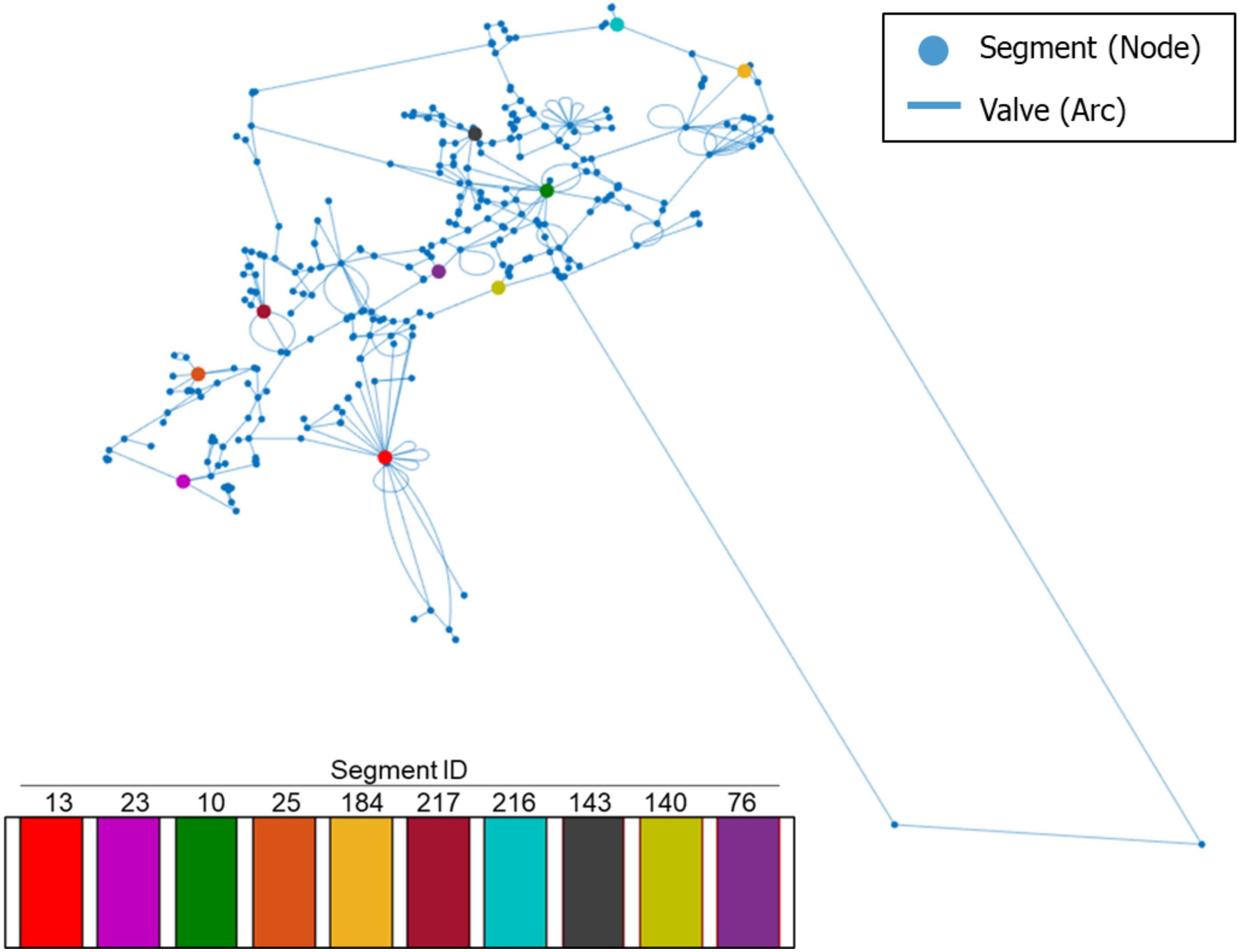

Figure B-21 KY6 with highlighted critical segments (TM) with Arc-Node topology

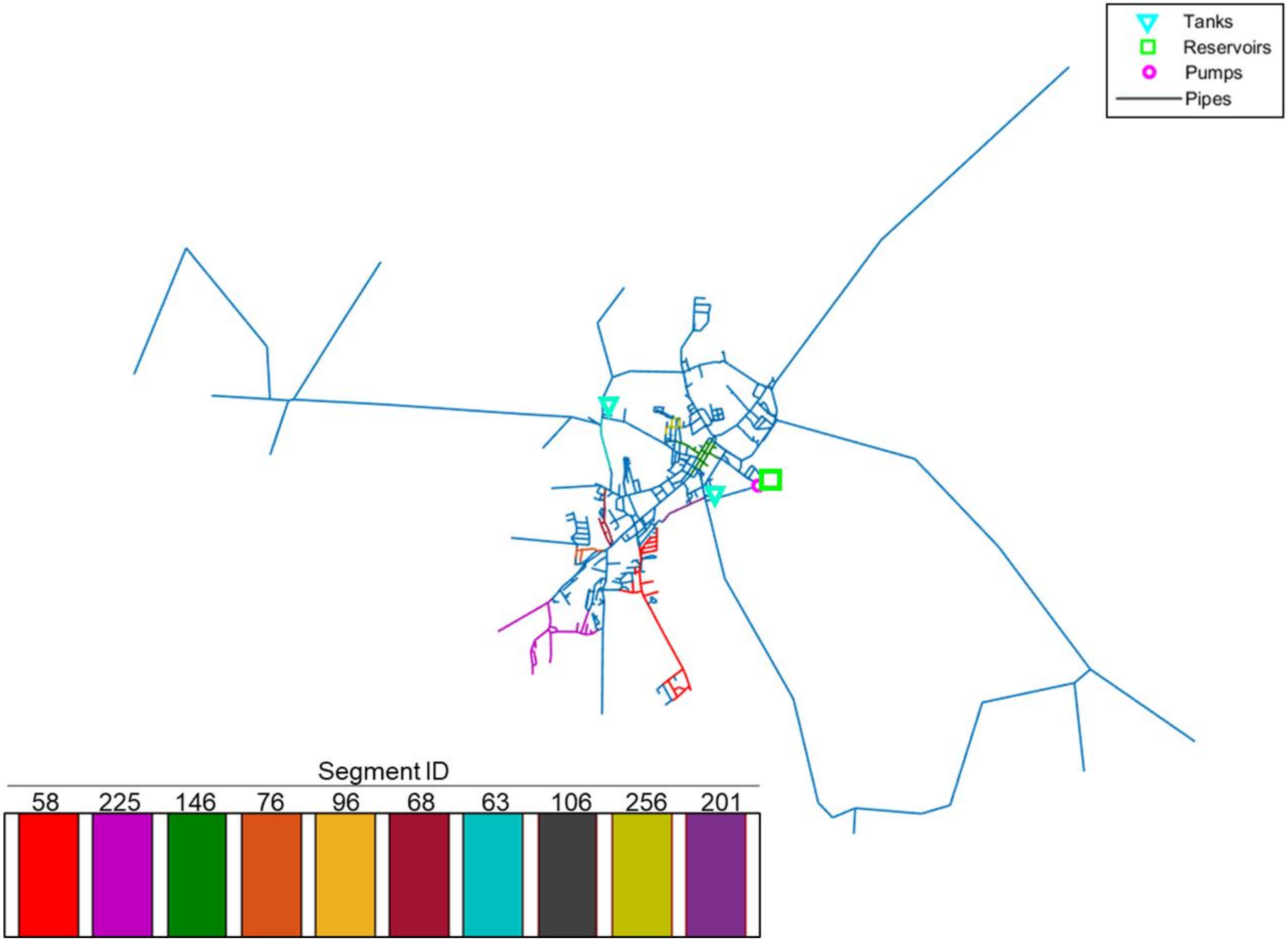

Figure B-22 KY18 with highlighted critical segments (PDND)

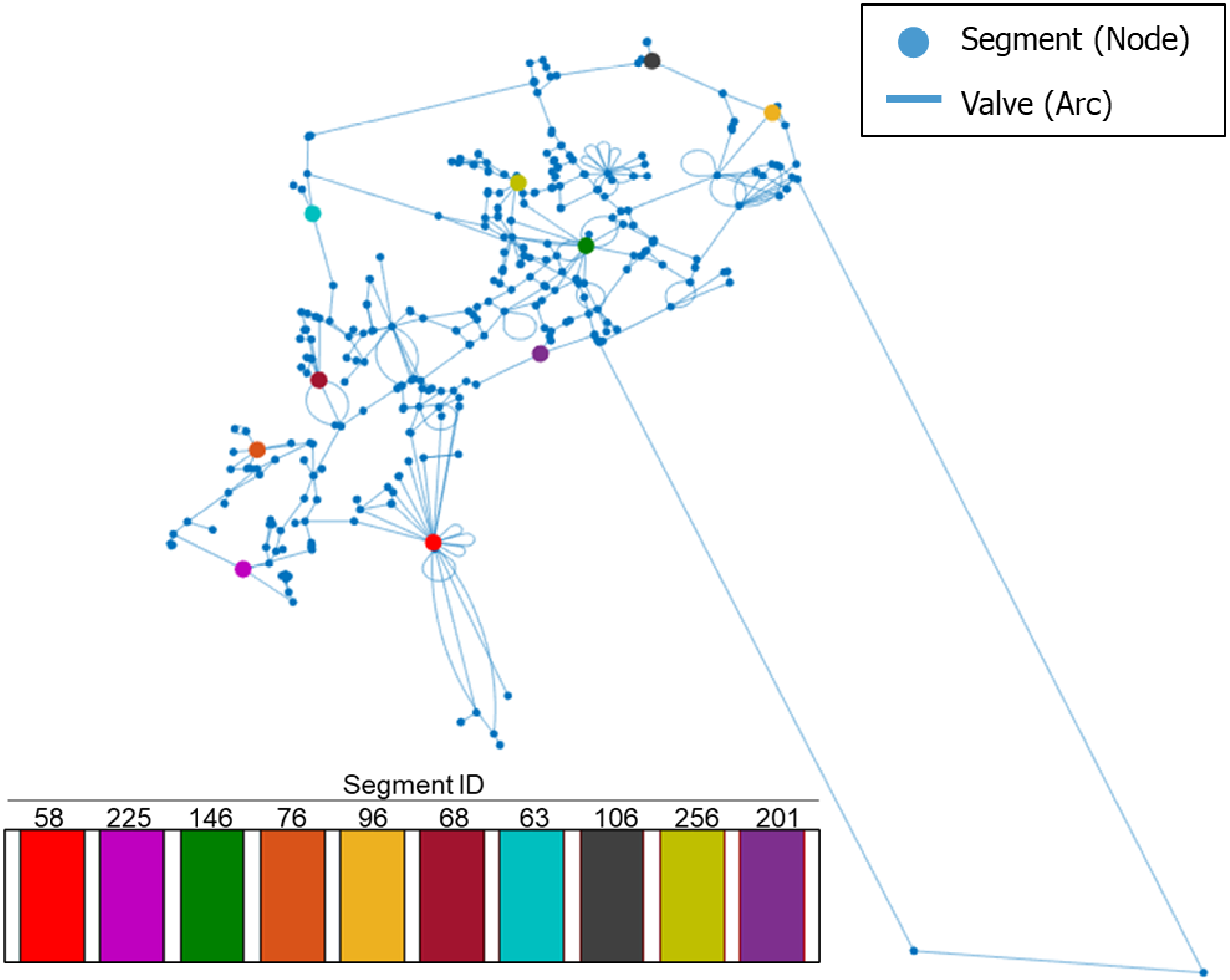

Figure B-23 KY18 with highlighted critical segments (PDND) with Arc-Node topology

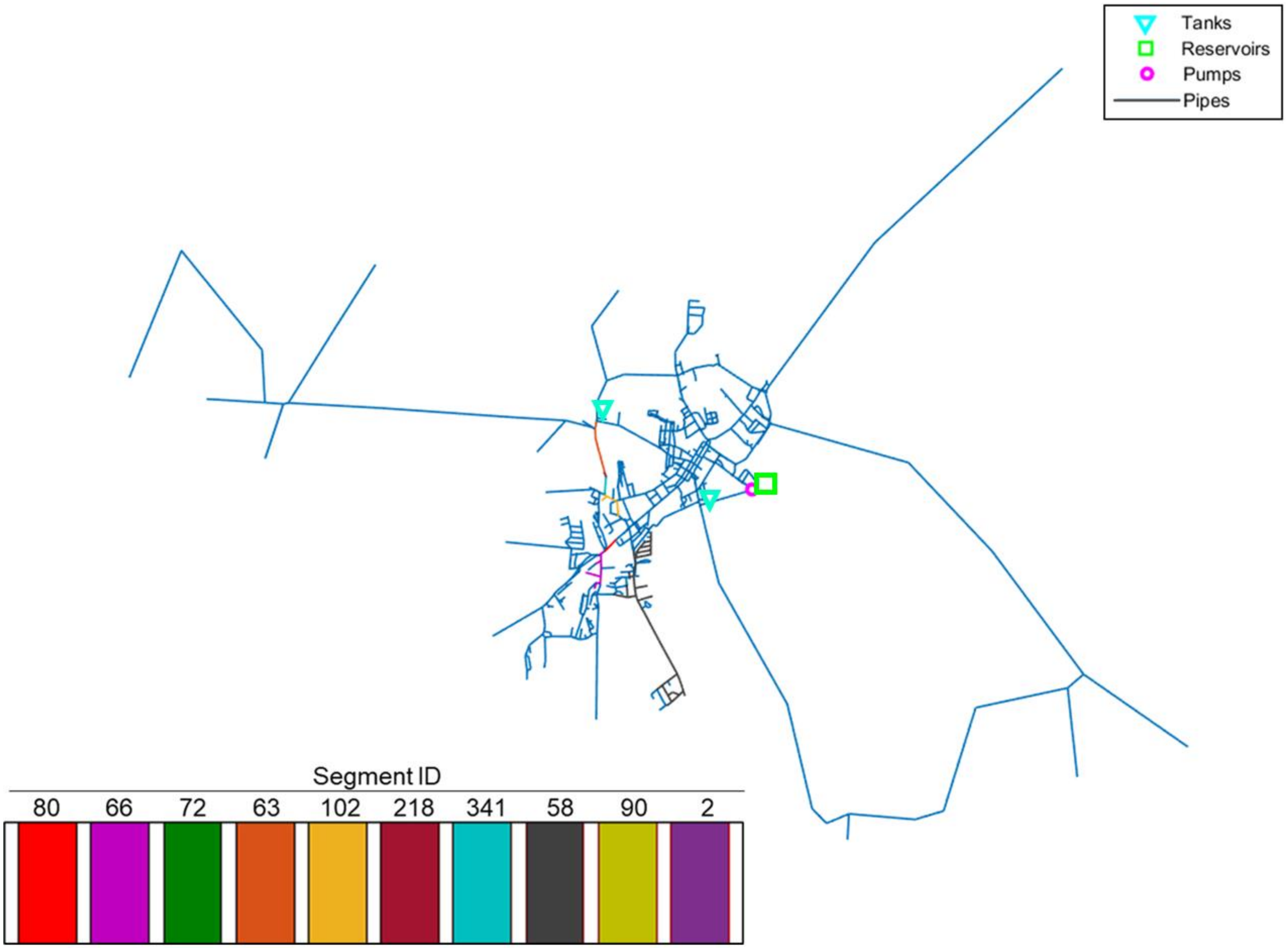

Figure B-24 KY18 with highlighted critical segments (PDFD)

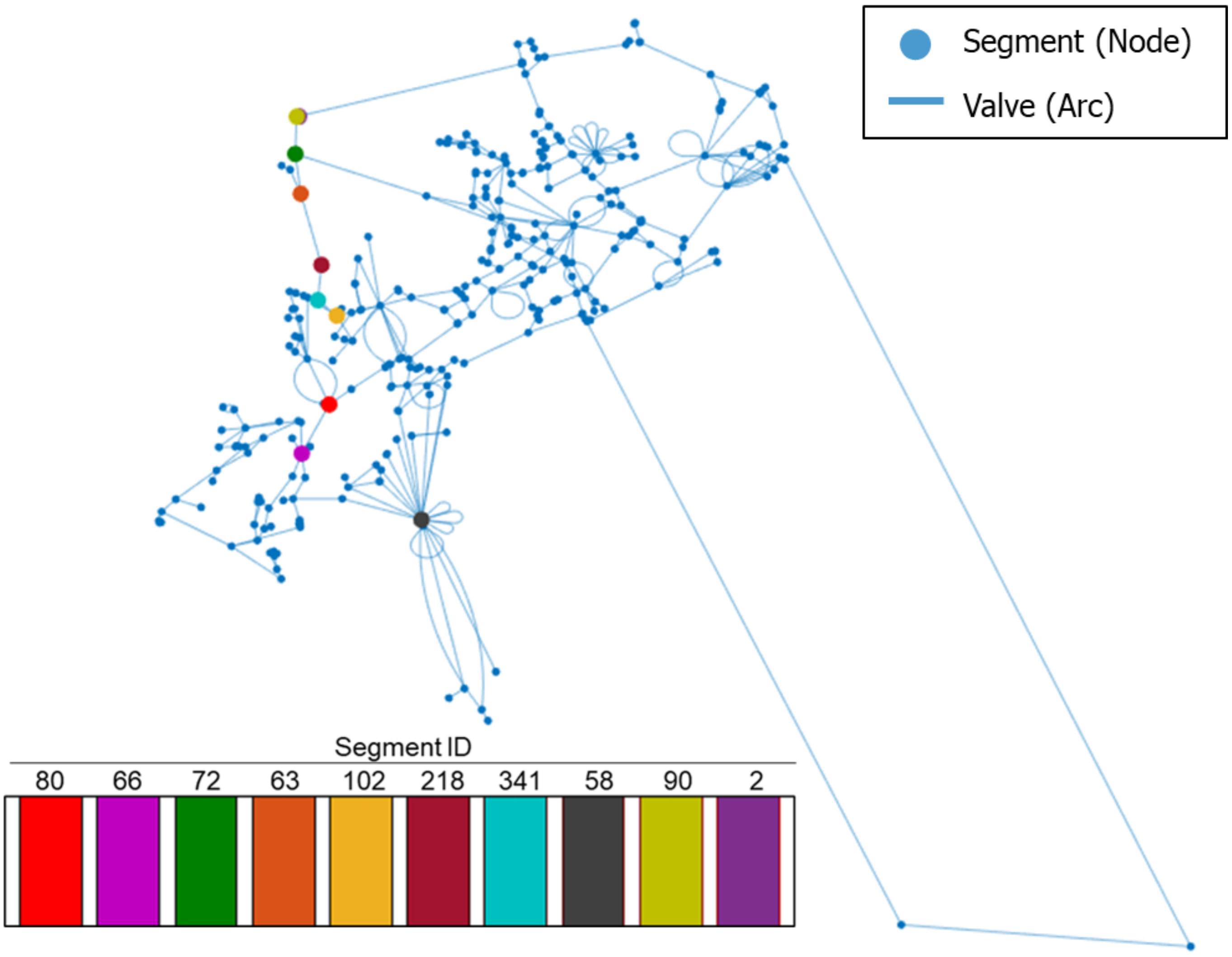

Figure B-25 KY18 with highlighted critical segments (PDFD) with Arc-Node topology

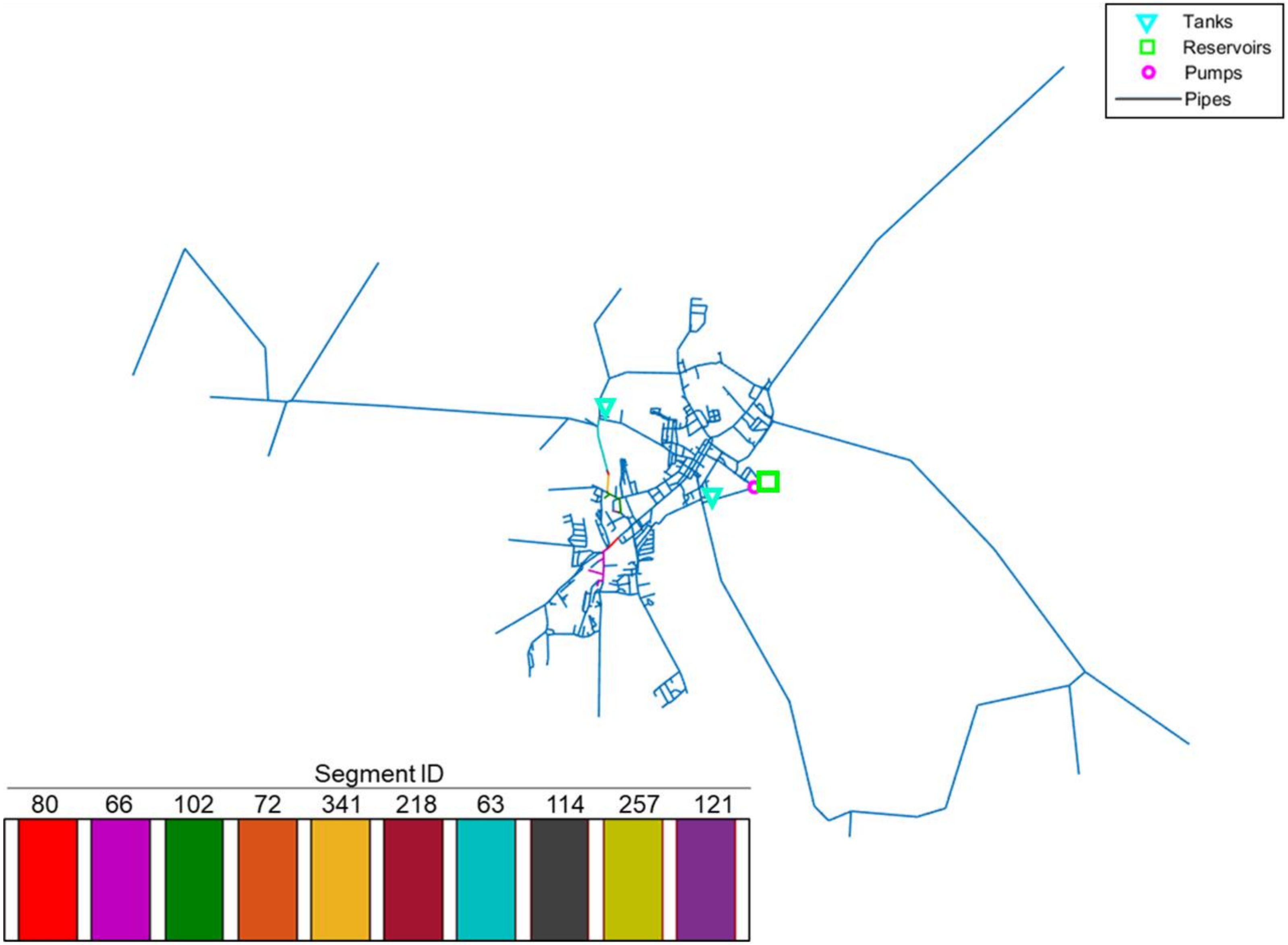

Figure B-26 KY18 with highlighted critical segments (PDHD)

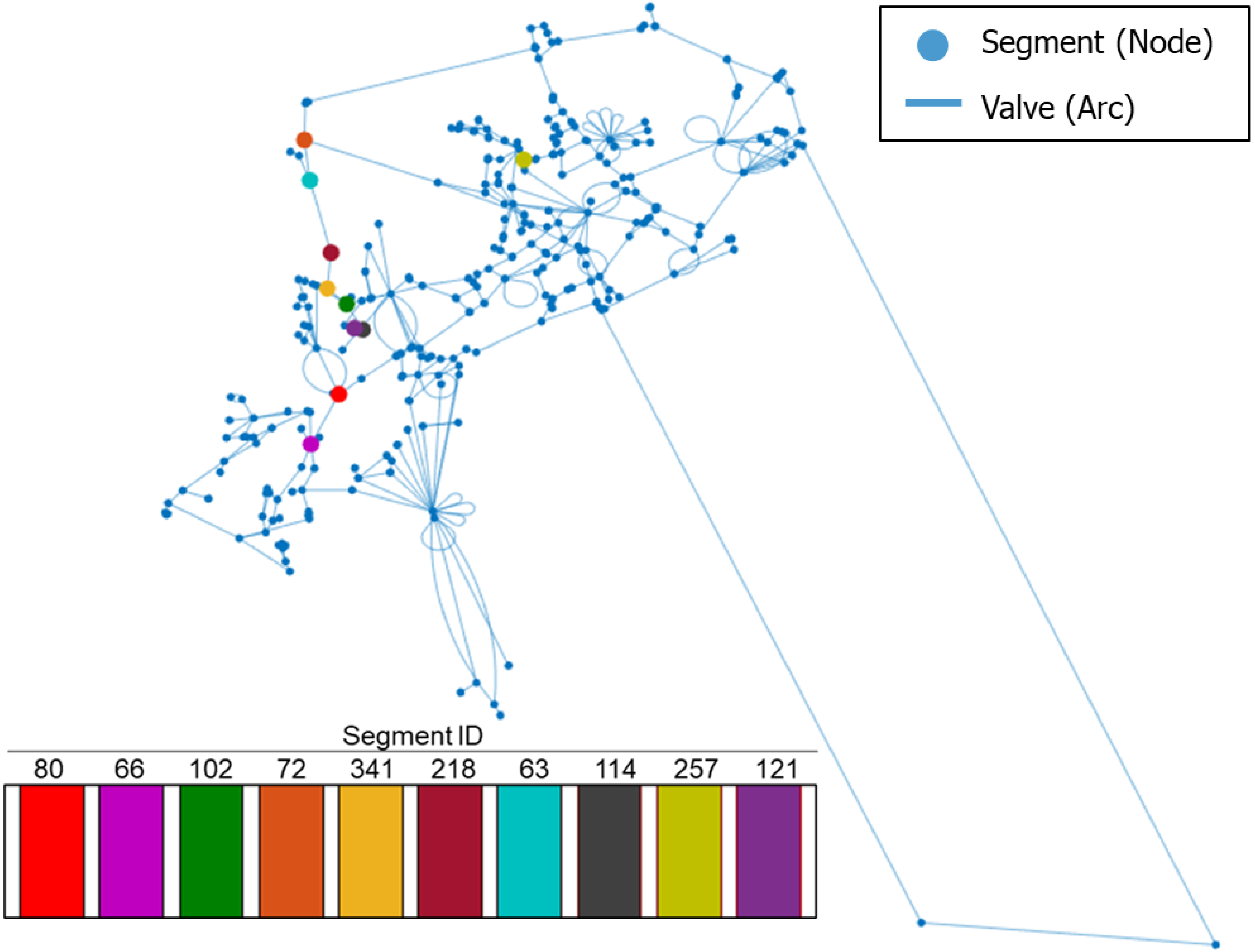

Figure B-27 KY18 with highlighted critical segments (PDHD) with Arc-Node topology

APPENDIX C. BAR PLOTS FOR TEST NETWORKS

This section presents the bar plots reporting the results of the segment-based assessment for each of the test networks (KY6, KY8, and KY18). For each network the following results are reported: (a) Topological Metric (TM), (b) Pressure Dependent Normal Demand (PDND) metric, (c) Pressure Dependent Fire Demand metric (PDFD) and (d) Pressure Dependent Hydrant Demand (PDHD) metric

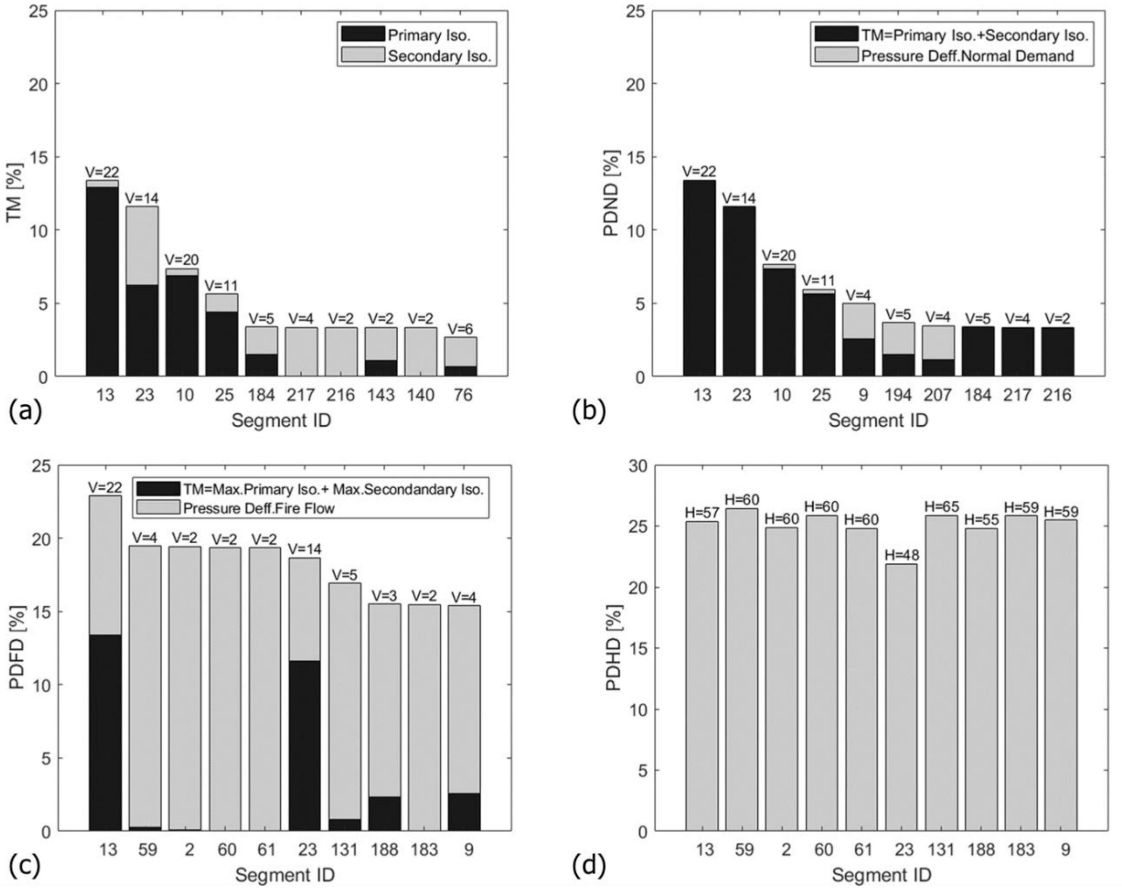

Figure C-1 KY6 Ten most critical segments for (a) Topological Metric (TM), (b) Pressure Dependent Normal Demand (PDND) metric, (c) Pressure Dependent Fire Demand metric (PDFD) and (d) Pressure Dependent Hydrant Demand (PDHD) metric

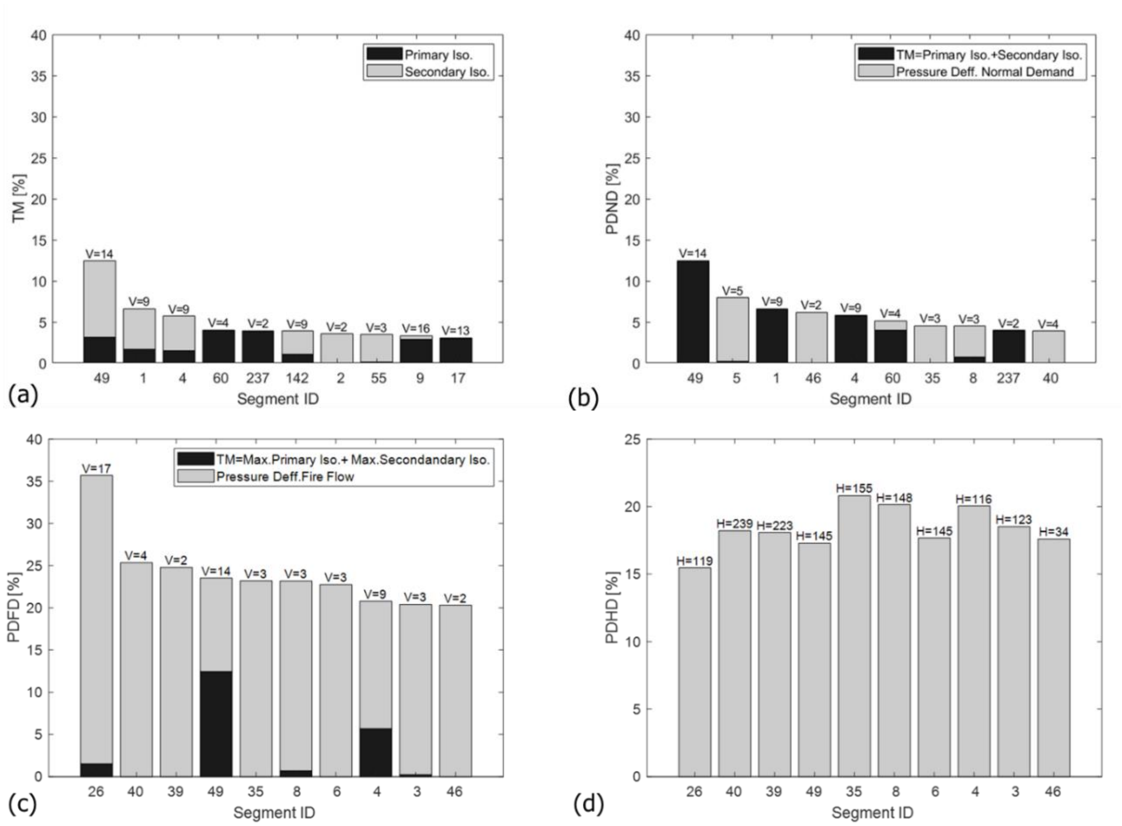

Figure C-2 KY8 Ten most critical segments for (a) Topological Metric (TM), (b) Pressure Dependent Normal Demand (PDND) metric, (c) Pressure Dependent Fire Demand metric (PDFD) and (d) Pressure Dependent Hydrant Demand (PDHD) metric

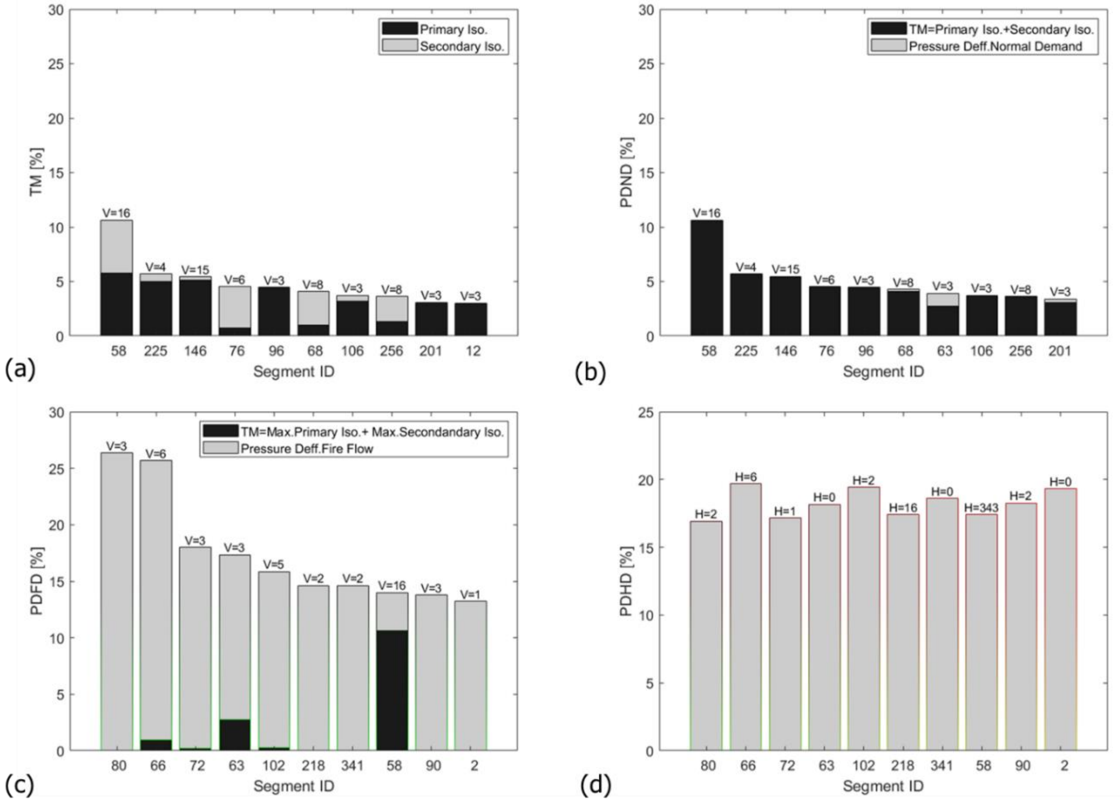

Figure C-3 KY18 Ten most critical segments for (a) Topological Metric (TM), (b) Pressure Dependent Normal Demand (PDND) metric, (c) Pressure Dependent Fire Demand metric (PDFD) and (d) Pressure Dependent Hydrant Demand (PDHD) metric

APPENDIX D. SEGMENT-BASED ASSESMENT RESULTS FOR TEST SYSTEMS WITH NEW VALVE CONFIGURATION

This section presents the tabulated results for each of the test networks (KY6, K8, and KY18) with the new valving layout defined by the optimization protocol (TM_s≤5%,NV_s≤10,NV_s≤5) .The results summarize the topologic properties of the networks, the overview of the delineated segments and isolation valve layout, and the characteristics of the critical segments identified by the segment-based assessment (TM, PDND,PDFD and PDHD)

Table D-1 Topologic Metrics for KY6 [TM≤5%]

Topologic Metric		Link-Node	Arc-Node
Link Density	q	0.003161	0.009074
Average Node Degree	K	2.260	2.386
Diameter	D	58363.75	
Average Path Length	l	23308.56	
Spectral Radius	λ^{A}_{1}	3.163	4.690
Spectral Gap	$\Delta\lambda^{A}$	0.09311	0.91809
Algebraic Connectivity	λ^{L}_{2}	0.00160	0.01025
Eigengap	Δ^{L}	0.26179	3.11861

Table D-2 Performance Indicators for KY6 [TM≤5%]

Performance Indicator		(ID)	Unit
Total Length	379816.5	(All)	ft
Number of Segments	264		
Average length of segment	1438.7	(All)	ft
Max.Segment Length	25845.9	207	ft
Min.Segment Length	0.2	81	ft
Length/valve ratio	1072.9	(All)	ft/valve
Average number of valves per pipe	0.4	(All)	valve
Total number of valves	354	(All)	valve
Number of external valves	338	(All)	valve
Number of internal valves	16	(All)	valve
Max.Number of valves to be closed by segment	14	10.1	valve/segment
Min.Number of valves to be closed by segment	1		valve/segment
Average number of valves to be closed by segment	1.3	(All)	valve/segment
Total Demand	1138.1	(All)	GPM
Total Customers	8194.3	(All)	customer
Average demand loss/valve	391.4	(All)	GPM/valve
Max.Demand loss/valve	105.2	AV-222	GPM/valve
Min.Demand loss/valve	66.2	AV-458	GPM/valve
Average customer loss/segment	49	(All)	customer/segment
Max.Customer loss/segment	396	10.1	customer/segment
Min.Customer loss/segment	0	1	customer/segment
Average Customer loss/valve	391	(All)	customer/valve
Max.Customer loss/valve	757	AV-222	customer/valve
Min.Customer loss/valve	66	AV-458	customer/valve

* For a customer, a household with 2.5 people on average and a daily demand per person of 80 gallons

Table D-3 Performance Metrics Summary for KY6 [TM≤5%]

	TM	PDND	PDFD	PDHD
Avg	0.60%(All)	0.73%(All)	11.94%(All)	27.9%(All)
Max	4.83% (s=10.2)	5.46% (s=9)	24.86%(s=131)	37.8%(s=234)
Min	0%(s=1)	0%(=3)	9.69%(s=177)	24.60%(s=224)
StD	0.95% (All)	1.08%(All)	2.43%(All)	1.57%(All)

Table D-4 KY6 [TM≤5%] Statistics of the Top Ten Critical Segments (TM metric)

Segment ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
10.2	12	37	7108	37	2	2	960	4	41	232
13.2.1	9	40	7861	40	3	4	1313	7	47	229
23.1.2.2	6	19	6008	20	8	22	13542	30	50	224
23.2	9	19	7967	20	7	26	5446	33	53	220
13.1.2	12	24	5249	24	1	1	488	2	26	233
25.2	7	12	1947	13	2	4	1068	6	19	234
184	5	27	10041	28	4	14	5611	18	46	222
217	4	5	13991	6	6	23	12519	29	35	228
216	2	1	170	2	5	22	12349	27	29	230
143	2	4	4588	5	3	15	7020	18	23	230

Table D-5 KY6 [TM≤5%] Statistics of the Top Ten Critical Segments (PDND metric)

Segment ID	N. Valves	Primary Pipe	Total Primary Length [ft]	Primary Isolated	N. Sec. Isolations	Secondary Pipe	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated	Available Hydrants
9	4	9	6739	10	0	0	0	0	10	235
10.2	12	37	7108	37	2	2	960.469	4	41	232
13.2.1	9	40	7861	40	3	4	1312.739	7	47	229
23.1.2.2	6	19	6008	20	8	22	13542.12	30	50	224
194	5	21	20493	22	1	1	845.309	2	24	230
207	4	20	25846	21	0	0	0	0	21	231
25.2	7	12	1947	13	2	4	1067.507	6	19	234
23.2	9	19	7967	20	7	26	5446.326	33	53	220
13.1.2	12	24	5249	24	1	1	488.44	2	26	233
184	5	27	10041	28	4	14	5610.564	18	46	222

Table D-6 KY6 [TM≤5%] Statistics of the Top Ten Critical Segments (PDFD metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
131	5	11	4312	12	0	0	0	0	12	232
183	2	1	2	2	0	0	0	0	2	235
2	2	3	1646	4	1	1	57	2	6	234
61	2	1	2	2	0	0	0	0	2	235
60	2	1	4	2	0	0	0	0	2	235
188	3	3	2695	4	4	9	3927	13	17	229
109	3	5	1390	6	0	0	0	0	6	235
59	4	8	2072	9	1	1	454	2	11	233
174	2	3	1852	4	0	0	0	0	4	234
9	4	9	6739	10	0	0	0	0	10	235

Table D-7 KY6 [TM≤5%] Statistics of the Top Ten Critical Segments (PDHD metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
234	3	4	8482	5	0	0	0	0	5	235
39	2	6	4252	7	0	0	0	0	7	232
119	5	9	2336	10	2	3	903	5	15	229
53	4	9	2705	10	0	0	0	0	10	230
49	6	10	1560	11	2	2	763	4	15	234
23.1.1	4	7	4298	8	0	0	0	0	8	234
32	2	1	836	2	0	0	0	0	2	235
149	3	12	3809	13	0	0	0	0	13	233
121	4	19	5445	19	0	0	0	0	19	232
207	4	20	25846	21	0	0	0	0	21	231

Table D-8 KY6 [TM≤5%] Statistics for Top Ten Critical Valves

Valve ID	Valve INDEX	TM [%]	Total Primary Length [ft]	Total Secondary Length [ft]	Total Length [ft]	Merged Segments	
~AV-222	1488	0.092435	30134.08	2631.023	27503.05	90	185
~AV-221	1487	0.089359	39673.37	11539.77	28133.6	134	234
~AV-1	1410	0.086548	17557.44	30.789	17526.65	80	226
V1	1409	0.086548	17538.65	9643.069	7895.586	13.1.2	13.2.2
~AV-22	1486	0.08523	30484.45	4835.088	25649.36	76	192
~AV-300	1547	0.082594	19542.18	1708.409	17833.77	45	147
~AV-95	1751	0.079694	23575.62	8438.682	15136.93	7	9
~AV-415	1637	0.078376	21707.17	2250.414	19456.76	90	113
~AV-275	1529	0.075652	35198.97	9040.537	26158.43	23.1.2.1	23.1.2.2
~AV-231	1493	0.075652	35945.96	92.269	35853.69	181	182

Table D-9 Topologic Metrics for KY6 [VN≤10]

Topologic Metric		Link-Node	Arc-Node
Link Density	q	0.003161	0.009161
Average Node Degree	K	2.260	2.400
Diameter	D	58363.75	
Average Path Length	l	23308.56	
Spectral Radius	$\lambda^{A}{}_{1}$	3.163	4.392
Spectral Gap	$\Delta\lambda^{A}$	0.09311	0.62037
Algebraic Connectivity	$\lambda^{L}{}_{2}$	0.00160	0.01054
Eigengap	Δ^{L}	0.26179	0.97329

Table D-10 Performance Indicators for KY6 [VN≤10]

Performance Indicator		(ID)	Unit
Total Length	379816.5	(All)	ft
Number of Segments	265		
Average length of segment	379816.5	(All)	ft
Max.Segment Length	25845.9	207	ft
Min.Segment Length	0.2	81	ft
Length/valve ratio	1066.9	(All)	ft/valve
Average number of valves per pipe	0.4	(All)	valve
Total number of valves	356	(All)	valve
Number of external valves	339	(All)	valve
Number of internal valves	17	(All)	valve
Max.Number of valves to be closed by segment	10	25.1	valve/segment
Min.Number of valves to be closed by segment	1	1	valve/segment
Average number of valves to be closed by segment	1.3	(All)	valve/segment
Total Demand	1138.1	(All)	GPM
Total Customers	8194.3	(All)	customer
Average demand loss/valve	710.4	(All)	GPM/valve
Max.Demand loss/valve	198.1	AV-190	GPM/valve
Min.Demand loss/valve	41.8	AV-458	GPM/valve
Average customer loss/segment	49	(All)	customer/segment
Max.Customer loss/segment	580	23.1	customer/segment
Min.Customer loss/segment	0	1	customer/segment
Average Customer loss/valve	710	(All)	customer/valve
Max.Customer loss/valve	1426	AV-190	customer/valve
Min.Customer loss/valve	301	AV-458	customer/valve

* For a customer, a household with 2.5 people on average and a daily demand per person of 80 gallons

Table D-11 Performance Metrics Summary for KY6 [VN≤10]

	TM	PDND	PDFD	PDHD
Avg	0.60%(All)	0.73% (All)	12.20% (All)	27.43% (All)
Max	7.08%(s=23.1)	7.09% (s=23.1)	27.12% (s=131)	37.35% (s=234)
Min	0%(s=1)	0%(s=3)	9.97%(s=177)	24.16%(s=224)
StD	0.97%(All)	1.09%(All)	2.54%(All)	1.54% (All)

Table D-12 KY6 [VN≤10] Statistics of the Top Ten Critical Segments (TM metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
23.1	7	36	13291	36	8	22	13542	30	66	220
13.2.1	9	40	7861	40	3	4	1313	7	47	229
23.2	9	19	7967	20	7	26	5446	33	53	220
25.2	7	12	1947	13	2	4	1068	6	19	234
184	5	27	10041	28	4	14	5611	18	46	222
217	4	5	13991	6	6	23	12519	29	35	228
216	2	1	170	2	5	22	12349	27	29	230
143	2	4	4588	5	3	15	7020	18	23	230
140	2	3	741	4	4	19	11608	23	27	230
13.2.2	8	26	4358	27	1	1	221	2	29	231

Table D-13 KY6 [VN≤10] Statistics of the Top Ten Critical Segments (PDND metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
23.1	7	36	13291	36	8	22	13542	30	66	220
9	4	9	6739	10	0	0	0	0	10	235
13.2.1	9	40	7861	40	3	4	1313	7	47	229
194	5	21	20493	22	1	1	845	2	24	230
207	4	20	25846	21	0	0	0	0	21	231
25.2	7	12	1947	13	2	4	1068	6	19	234
23.2	9	19	7967	20	7	26	5446	33	53	220
184	5	27	10041	28	4	14	5611	18	46	222
217	4	5	13991	6	6	23	12519	29	35	228
143	2	4	4588	5	3	15	7020	18	23	230

Table D-14 KY6 [VN≤10] Statistics of the Top Ten Critical Segments (PDFD metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
131	5	11	4312	12	0	0	0	0	12	232
183	2	1	2	2	0	0	0	0	2	235
188	3	3	2695	4	4	9	3927	13	17	229
109	3	5	1390	6	0	0	0	0	6	235
59	4	8	2072	9	1	1	454	2	11	233
2	2	3	1646	4	1	1	57	2	6	234
61	2	1	2	2	0	0	0	0	2	235
60	2	1	4	2	0	0	0	0	2	235
174	2	3	1852	4	0	0	0	0	4	234
9	4	9	6739	10	0	0	0	0	10	235

Table D-15 KY6 [VN≤10] Statistics of the Top Ten Critical Segments (PDHD metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length	Secondary Isolated	Total Isolated Nodes	Available Hydrants
234	3	4	8482	5	0	0	0	0	5	235
39	2	6	4252	7	0	0	0	0	7	232
119	5	9	2336	10	2	3	903	5	15	229
53	4	9	2705	10	0	0	0	0	10	230
49	6	10	1560	11	2	2	763	4	15	234
32	2	1	836	2	0	0	0	0	2	235
149	3	12	3809	13	0	0	0	0	13	233
121	4	19	5445	19	0	0	0	0	19	232
207	4	20	25846	21	0	0	0	0	21	231
98	4	14	6188	15	5	6	166	11	26	222

Table D-16 KY6 [VN≤10] Statistics for Top Ten Critical Valves

Valve ID	Valve INDEX	TM [%]	Total Primary Length [ft]	Total Secondary Length [ft]	Total Length [ft]	Merged Segments	
~AV-190	1472	0.174062	58845.16	1067.507	57777.66	197	198
~AV-187	1469	0.167209	56957.41	2614.07	54343.34	25.2	198
~AV-189	1471	0.166769	58168.32	3218.442	54949.88	25.2	249
~AV-1	1414	0.166593	46117.38	30.789	46086.59	80	226
V1	1413	0.166593	46098.59	7405.889	38692.7	13.1.2.1	13.2.2
~AV-108	1416	0.165715	43830.36	1990.376	41839.98	116	10.2.2
V2	1412	0.162639	46750.74	4339.607	42411.13	10.1.2	10.2.2
~AV-184	1466	0.160794	57204.61	1924.196	55280.41	200	10.2.2
~AV-182	1464	0.160794	57257.24	1976.825	55280.41	201	10.2.2
'V3'	1411	0.158861	47118.29	7617.319	39500.97	13.1.1	13.1.2.1

Table D-17 Topologic Metrics for KY6 [VN≤5]

Topologic Metric		Link-Node	Arc-Node
Link Density	q	0.003161	0.009161
Average Node Degree	K	2.260	2.457
Diameter	D	58363.75	
Average Path Length	l	23308.56	
Spectral Radius	λ^A_1	3.163	3.745
Spectral Gap	$\Delta\lambda^A$	0.09311	0.22862
Algebraic Connectivity	λ^L_2	0.00160	0.00815
Eigengap	Δ^L	0.26179	0.48633

Table D-18 Performance Indicators for KY6 [VN≤5]

Performance Indicator		(ID)	Unit
Total Length	379816.5	(All)	ft
Number of Segments	315		
Average length of segment	1205.8	(All)	ft
Max.Segment Length	25845.9	250	ft
Min.Segment Length	0.2	91	ft
Length/valve ratio	930.9	(All)	ft/valve
Average number of valves per pipe	0.5	(All)	valve
Total number of valves	408	(All)	valve
Number of external valves	402	(All)	valve
Number of internal valves	6	(All)	valve
Max.Number of valves to be closed by segment	6	10.1.1.1.1	valve/segment
Min.Number of valves to be closed by segment	1	1	valve/segment
Average number of valves to be closed by segment	1.3	(All)	valve/segment
Total Demand	1138.1	(All)	GPM
Total Customers	8194.3	(All)	customer
Average demand loss/valve	412.0	(All)	GPM/valve
Max.Demand loss/valve	95.4	V32	GPM/valve
Min.Demand loss/valve	0.0	V62	GPM/valve
Average customer loss/segment	41	(All)	customer/segment
Max.Customer loss/segment	277	184	customer/segment
Min.Customer loss/segment	0	1	customer/segment
Average Customer loss/valve	412	(All)	customer/valve
Max.Customer loss/valve	687	V32	customer/valve
Min.Customer loss/valve	0	V62	customer/valve

* For a customer, a household with 2.5 people on average and a daily demand per person of 80 gallons

Table D-19 Performance Metrics Summary for KY6 [VN≤5]

	TM	PDND	PDFD	PDHD
Avg	0.50% (All)	0.59% (All)	0.59% (All)	23.85% (All)
Max	3.38% (s=184)	4.98% (s=9)	18.49% (s=2)	27.35% (s=23.1.1)
Min	0%(s=1)	0%(s=3)	5.73%(s=110)	22.27%(s=6)
StD	0.72%(All)	0.82% (All)	1.91%(All)	0.43%(All)

Table D-20 KY6 [VN≤5] Statistics of the Top Ten Critical Segments (TM metric)

Seg. ID	N. Valves	Prim. Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Sec. Pipe Elements	Total Sec. Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
184	5	29	10053	30	4	16	5623	20	50	226
217	4	5	13991	6	6	24	12525	30	36	229
216	2	1	170	2	5	23	12355	28	30	231
143	2	4	4588	5	3	16	7026	19	24	231
140	2	3	741	4	4	20	11614	24	28	231
23.1.2.2.2.2	4	8	3037	9	7	24	12510	31	40	229
212	2	1	346	2	4	21	11649	25	27	232
151	2	1	216	2	5	22	11995	27	29	232
150	2	7	1969	8	3	14	9679	17	25	232
9	4	9	6739	10	0	0	0	0	10	235

Table D-21 KY6 [VN≤5] Statistics of the Top Ten Critical Segments (PDND metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Sec. Pipe Elements	Total Sec. Length [ft]	Sec. Iso. Nodes	Total Isolated Nodes	Available Hydrants
9	4	9	6739	10	0	0	0	0	10	235
194	5	21	20493	22	1	1	845	2	24	230
207	4	22	25858	23	0	0	0	0	23	233
184	5	29	10053	30	4	16	5623	20	50	226
217	4	5	13991	6	6	24	12525	30	36	229
216	2	1	170	2	5	23	12355	28	30	231
143	2	4	4588	5	3	16	7026	19	24	231
140	2	3	741	4	4	20	11614	24	28	231
23.1.2.2.2.2	4	8	3037	9	7	24	12510	31	40	229
7	4	5	1699	6	0	0	0	0	6	235

Table D-22 KY6 [VN≤5] Statistics of the Top Ten Critical Segments (PDFD metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Sec. Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
2	2	4	1652	5	1	1	57	2	7	235
59	4	10	2084	11	1	1	454	2	13	235
60	2	1	4	2	0	0	0	0	2	235
61	2	1	2	2	0	0	0	0	2	235
131	5	14	4330	15	0	0	0	0	15	235
188	3	3	2695	4	4	13	3951	17	21	233
183	2	1	2	2	0	0	0	0	2	235
109	3	5	1390	6	0	0	0	0	6	235
9	4	9	6739	10	0	0	0	0	10	235
194	5	21	20493	22	1	1	845	2	24	230

Table D-23 KY6 [VN≤5] Statistics of the Top Ten Critical Segments (PDHD metric)

Seg. ID	N. Valves	Prim. Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Seco. Pipe Elements	Total Secondary Length [ft]	Sec. Iso. Nodes	Total Isolated Nodes	Available Hydrants
23.1.1	4	7	4298	8	0	0	0	0	8	234
131	5	14	4330	15	0	0	0	0	15	235
217	4	5	13991	6	6	24	12525	30	36	229
20.2.2	4	3	151	4	0	0	0	0	4	233
79.1	5	10	702	11	3	11	3196	14	25	231
25.1.2.2	4	4	955	5	0	0	0	0	5	233
25.1.2.1.2	4	4	849	5	0	0	0	0	5	233
184	5	29	10053	30	4	16	5623	20	50	226
10.2.1.1.1.1.1	5	5	752	6	0	0	0	0	6	232
95	4	11	1619	12	1	1	231	2	14	235

Table D-24 KY6 [VN≤5] Statistics for Top Ten Critical Valves

Valve ID	Valve INDEX	TM [%]	Total Primary Length [ft]	Total Secondary Length [ft]	Total Length [ft]	Merged Segments	
V32	1486	0.083824	28824.42	3517.992	25306.43	18.1	18.2
~AV-22	1594	0.080485	30739.15	3179.138	27560.02	76.1.1	192
~AV-222	1596	0.079782	29848.46	2631.023	27217.43	90	185
~AV-221	1595	0.079255	39747.94	11539.77	28208.16	134	234
~AV-392	1725	0.078376	31226.56	1834.301	29392.26	103	13.1.2.2.2
~AV-11	1521	0.075916	27799.24	4389.541	23409.7	13.1.1.1	103
~AV-231	1601	0.075652	35945.96	92.269	35853.69	181	182
~AV-230	1600	0.075652	37982.22	42.39	37939.83	182	195
V4	1514	0.075125	28703.99	1867.53	26836.46	10.1.1.2	10.1.2.1
~AV-275	1637	0.075037	49374.89	4835.823	44539.07	23.1.2.1	23.1.2.2.1.1.1

Table D-25 Topologic Metrics for KY8 [TM≤5%]

Topologic Metric		Link-Node	Arc-Node
Link Density	q	0.001817	0.009409
Average Node Degree	K	2.416	2.813
Diameter	D	63527.95	
Average Path Length	l	28060.94	
Spectral Radius	λ^A_1	3.529	4.561
Spectral Gap	$\Delta\lambda^A$	0.10474	0.09955
Algebraic Connectivity	λ^L_2	0.00111	0.01075
Eigengap	Δ^L	0.39205	1.81047

Table D-26 Performance Indicators for KY8 [TM≤5%]

Performance Indicator		(ID)	Unit
Total Length	774233.3	(All)	ft
Number of Segments	300		
Average length of segment	2580.8	(All)	ft
Max.Segment Length	32710.2	60	ft
Min.Segment Length	103.9	265	ft
Length/valve ratio	1567.3	(All)	ft/valve
Average number of valves per pipe	0.3	(All)	valve
Total number of valves	494	(All)	valve
Number of external valves	477	(All)	valve
Number of internal valves	11	(All)	valve
Max.Number of valves to be closed by segment	17	26	valve/segment
Min.Number of valves to be closed by segment	1	7	valve/segment
Average number of valves to be closed by segment	1.6	(All)	valve/segment
Total Demand	1711.4	(All)	GPM
Total Customers	12321.9	(All)	customer
Average demand loss/valve	6.0	(All)	GPM/valve
Max.Demand loss/valve	299.3	AV-683	GPM/valve
Min.Demand loss/valve	97.3	V6	GPM/valve
Average customer loss/segment	54	(All)	customer/segment
Max.Customer loss/segment	495	60	customer/segment
Min.Customer loss/segment	0	6	customer/segment
Average Customer loss/valve	6	(All)	customer/valve
Max.Customer loss/valve	2155	AV-683	customer/valve
Min.Customer loss/valve	700	V6	customer/valve

* For a customer, a household with 2.5 people on average and a daily demand per person of 80 gallons

Table D-27 Performance Metrics Summary for KY8 [TM≤5%]

	TM	PDND
Avg	0.44%(All)	0.65%(All)
Max	4%(s=60)	12.5%(s=49.1.1.1)
Min	0%(s=6)	0%(s=7)
StD	1.04%(All)	1.20%(All)

Table D-28 KY8 [TM≤5%] Statistics of the Top Ten Critical Segments (TM metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Sec. Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
60	4	82	32710	73	0	0	0	0	73	792
237	3	42	30772	41	0	0	0	0	41	789
142	4	30	7619	29	9	53	19335	62	91	755
2	2	3	1613	4	7	57	31173	61	65	764
55	3	3	1692	4	6	54	29481	57	61	765
9	16	70	18208	70	9	14	4850	23	93	750
17	13	61	16957	54	1	1	984	2	56	773
73	2	36	20171	33	0	0	0	0	33	790
65	8	33	11759	34	7	19	7083	26	60	764
266	3	3	1444	4	1	38	17520	36	40	789

Table D-29 KY8 [TM≤5%] Statistics of the Top Ten Critical Segments (PDND metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Sec. Pipe Elements	Total Secondary Length [ft]	Sec. Iso. Nodes	Total Isolated Nodes	Available Hydrants
49.1.1.1	14	12	5984	13	0	0	0	0	13	790
5	5	13	1771	14	0	0	0	0	14	790
60	4	82	32710	73	0	0	0	0	73	792
35	3	3	2933	4	0	0	0	0	4	793
8	3	5	8165	6	1	7	3690	8	14	790
237	3	42	30772	41	0	0	0	0	41	789
40	4	4	929	5	0	0	0	0	5	793
142	4	30	7619	29	9	53	19335	62	91	755
46	2	2	3988	3	0	0	0	0	3	793
6	3	10	11279	11	0	0	0	0	11	788

Table D-30 KY8 [TM≤5%] Statistics for Top Ten Critical Valves

Valve ID	Valve INDEX	TM [%]	Total Primary Length [ft]	Total Secondary Length [ft]	Total Length [ft]	Merged Segments	
~AV-460	3308	17.53%	102139.3	5427.2	96712.1	138	141
~AV-462	3309	17.18%	102505.5	5369.9	97135.6	137	268
~AV-465	3310	17.07%	102747.7	4025.1	98722.6	136	137
~AV-107	3051	17.06%	96041.21	9318.1	86723.1	10	14
~AV-469	3312	16.86%	101940.9	1846.9	100094.0	29	255
~AV-467	3311	16.84%	102439.6	2418.0	100021.6	136	176
~AV-244	3152	16.81%	98696.36	9088.1	89608.3	132	189
~AV-239	3149	16.58%	97479.31	4726.8	92752.5	189	191
~AV-127	3065	16.53%	119183.4	44456.4	74727.0	1.2	237
~AV-189	3111	16.53%	98084.55	3911.3	94173.3	210	243

Table D-31 Topologic Metrics for KY8 [VN≤10]

Topologic Metric		Link-Node	Arc-Node
Link Density	q	0.001817	0.009325
Average Node Degree	K	2.416	2.853
Diameter	D	63527.95	
Average Path Length	l	28060.94	
Spectral Radius	λ^{A}_{1}	3.529	4.475
Spectral Gap	$\Delta\lambda^{A}$	0.10474	0.21262
Algebraic Connectivity	λ^{L}_{2}	0.00111	0.01059
Eigengap	Δ^{L}	0.39205	2.15977

Table D-32 Performance Indicators for KY8 [VN≤10]

Performance Indicator		(ID)	Unit
Total Length	774233.3	(All)	ft
Number of Segments	307		
Average length of segment	2521.9	(All)	ft
Max.Segment Length	32710.2	60	ft
Min.Segment Length	103.9	265	ft
Length/valve ratio	1536.2	(All)	ft/valve
Average number of valves per pipe	0.3	(All)	valve
Total number of valves	504	(All)	valve
Number of external valves	499	(All)	valve
Number of internal valves	13	(All)	valve
Max.Number of valves to be closed by segment	13	125.1.2.1.1	valve/segment
Min.Number of valves to be closed by segment	1	7	valve/segment
Average number of valves to be closed by segment	1.6	(All)	valve/segment
Total Demand	1711.4	(All)	GPM
Total Customers	12321.9	(All)	customer
Average demand loss/valve	1980.1	(All)	GPM/valve
Max.Demand loss/valve	342.2	AV-693	GPM/valve
Min.Demand loss/valve	13.8	V13	GPM/valve
Average customer loss/segment	60	(All)	customer/segment
Max.Customer loss/segment	1531	49.1	customer/segment
Min.Customer loss/segment	0	6	customer/segment
Average Customer loss/valve	1980	(All)	customer/valve
Max.Customer loss/valve	2464	AV-693	customer/valve
Min.Customer loss/valve	100	V13	customer/valve

* For a customer, a household with 2.5 people on average and a daily demand per person of 80 gallons

Table D-33 Performance Metrics Summary for KY8 [VN≤10]

	TM	PDND
Avg	0.49% (All)	0.65% (All)
Max	12.45% (s=49.1)	12.47% (s=49.1)
Min	0%(s=6)	0%(s=7)
StD	1.04%(All)	1.25%(All)

Table D-34 KY8 [VN≤10] Statistics of the Top Ten Critical Segments (TM metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Sec. Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
49.1	8	35	12614	35	30	224	68639	246	281	742
1	9	40	20715	35	5	56	37438	59	94	768
4	9	33	14602	33	10	82	28816	88	121	749
60	4	82	32710	73	0	0	0	0	73	792
237	2	42	30772	41	0	0	0	0	41	789
142	9	30	7619	29	9	53	19335	62	91	755
2	2	3	1613	4	7	57	31173	61	65	764
55	3	3	1692	4	6	54	29481	57	61	765
73	2	36	20171	33	0	0	0	0	33	790
65	8	33	11759	34	7	19	7083	26	60	764

Table D-35 KY8 [VN≤10] Statistics of the Top Ten Critical Segments (PDND metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
49.1	8	35	12614	35	30	224	68639	246	281	742
5	5	13	1771	14	0	0	0	0	14	790
1	9	40	20715	35	5	56	37438	59	94	768
4	9	33	14602	33	10	82	28816	88	121	749
60	4	82	32710	73	0	0	0	0	73	792
35	3	3	2933	4	0	0	0	0	4	793
8	3	5	8165	6	1	7	3690	8	14	790
237	2	42	30772	41	0	0	0	0	41	789
40	4	4	929	5	0	0	0	0	5	793
142	9	30	7619	29	9	53	19335	62	91	755

Table D-36 KY8 [VN≤10] Statistics for Top Ten Critical Valves

Valve ID	Valve INDEX	TM [%]	Total Primary Length [ft]	Total Secondary Length [ft]	Total Length [ft]	Merged Segments	
~AV-693	3510	0.200408	144604	5144.686	139459.3	40	41
~AV-692	3509	0.199148	139501.3	5323.546	134177.8	41	33.2
~AV-694	3511	0.197784	139390.8	5213.084	134177.8	40	33.2
~AV-7	3514	0.193555	130921.6	2366.464	128555.1	38	253
~AV-239	3169	0.192559	104224.5	4726.846	99497.66	189	191
~AV-125	3083	0.191792	129541.3	3604.088	125937.2	234	286
~AV-138	3094	0.191089	121764.3	4163.545	117600.8	227	228
~AV-691	3508	0.190738	133514.8	51571.64	81943.12	1	237
~AV-234	3164	0.19048	103780	1751.924	102028	194	195
~AV-704	3517	0.190433	132011.3	9034.378	122976.9	35	36

Table D-37 Topologic Metrics for KY8 [VN≤5]

Topologic Metric		Link-Node	Arc-Node
Link Density	q	0.001817	0.007257
Average Node Degree	K	2.416	2.903
Diameter	D	63527.95	
Average Path Length	l	28060.94	
Spectral Radius	λ^A_1	3.529	4.511
Spectral Gap	$\Delta\lambda^A$	0.10474	0.46917
Algebraic Connectivity	λ^L_2	0.00111	0.00738
Eigengap	Δ^L	0.39205	5.12152

Table D-38 Performance Indicators for KY8 [VN≤5]

Performance Indicator		(ID)	Unit
Total Length	774233.3	(All)	ft
Number of Segments	401		
Average length of segment	1930.8	(All)	ft
Max.Segment Length	32710.2	60	ft
Min.Segment Length	86.1	171.1.2	ft
Length/valve ratio	1265.1	(All)	ft/valve
Average number of valves per pipe	0.3	(All)	valve
Total number of valves	612	(All)	valve
Number of external valves	612	(All)	valve
Number of internal valves	0	(All)	valve
Max.Number of valves to be closed by segment	13	125.1.2.1.1	valve/segment
Min.Number of valves to be closed by segment	1	7	valve/segment
Average number of valves to be closed by segment	1.5	(All)	valve/segment
Total Demand	1711.4	(All)	GPM
Total Customers	12321.9	(All)	customer
Average demand loss/valve	822.1	(All)	GPM/valve
Max.Demand loss/valve	185.1	AV-692	GPM/valve
Min.Demand loss/valve	3.1	V124	GPM/valve
Average customer loss/segment	42	(All)	customer/segment
Max.Customer loss/segment	700	4.1	customer/segment
Min.Customer loss/segment	0	6	customer/segment
Average Customer loss/valve	822	(All)	customer/valve
Max.Customer loss/valve	1333	AV-692	customer/valve
Min.Customer loss/valve	23	V124	customer/valve

* For a customer, a household with 2.5 people on average and a daily demand per person of 80 gallons

Table D-39 Performance Metrics Summary for KY8 [VN≤5]

	TM	PDND
Avg	0.34% (All)	0.51% (All)
Max	5.70% (s=4.1)	12.47% (s=49.1.1.1.1)
Min	0%(s=6)	0%(s=7)
StD	0.58%(All)	1.04%(All)

Table D-40 KY8 [VN≤5] Statistics of the Top Ten Critical Segments (TM metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
4.1	5	23	9553	23	12	90	33841	98	121	745
60	4	82	32710	73	0	0	0	0	73	792
237	2	42	30772	41	0	0	0	0	41	789
2	2	3	1613	4	7	57	31173	61	65	764
55	3	3	1692	4	6	54	29481	57	61	765
73	2	36	20171	33	0	0	0	0	33	790
65.2	4	14	5528	15	9	36	13290	45	60	760
266	3	3	1444	4	1	38	17520	36	40	789
56	1	38	17520	36	0	0	0	0	36	792
213.1	4	6	1012	7	5	37	7339	42	49	792

Table D-41 KY8 [VN≤5] Statistics of the Top Ten Critical Segments (PDND metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
49.1.1.1.1	4	4	2138	5	0	0	0	0	5	792
5	5	13	1771	14	0	0	0	0	14	790
4.1	5	23	9553	23	12	90	33841	98	121	745
60	4	82	32710	73	0	0	0	0	73	792
35	3	3	2933	4	0	0	0	0	4	793
8	3	5	8165	6	1	7	3690	8	14	790
237	2	42	30772	41	0	0	0	0	41	789
40	4	4	929	5	0	0	0	0	5	793
46	2	2	3988	3	0	0	0	0	3	793
6	3	10	11279	11	0	0	0	0	11	788

Table D-42 KY8 [VN≤5] Statistics for Top Ten Critical Valves

Valve ID	Valve INDEX	TM [%]	Total Primary Length [ft]	Total Secondary Length [ft]	Total Length [ft]	Merged segments	
~AV-692	3725	10.8%	91044.63	3336.07	87708.56	42	33.2.1
~AV-693	3726	10.8%	94826.37	5144.686	89681.68	40	41
~AV-694	3727	10.7%	90934.17	3225.608	87708.56	40	33.2.1
~AV-691	3724	10.2%	87222.47	37911.38	49311.09	1.1	237
~AV-736	3753	9.9%	87339.47	3147.039	84192.43	18.1.1	288
~AV-738	3755	9.8%	87616.76	3972.611	83644.15	19.2	20
~AV-735	3752	9.7%	88167.31	6108.549	82058.77	18.1.1	279
~AV-739	3756	9.7%	87374.44	3397.38	83977.06	19.1	20
~AV-733	3751	9.7%	87581.04	3787.851	83793.18	21	22
~AV-662	3701	9.6%	70296.32	18988.3	51308.02	56	266

Table D-43 Topologic Metrics for KY18 [TM≤5%]

Topologic Metric		Link-Node	Arc-Node
Link Density	q	0.003098	0.007312
Average Node Degree	K	2.355	2.544
Diameter	D	97237.95	
Average Path Length	l	23988.27	
Spectral Radius	λ^A_1	3.193	4.359
Spectral Gap	$\Delta\lambda^A$	0.13084	0.41966
Algebraic Connectivity	λ^L_2	0.00149	0.00495
Eigengap	Δ^L	0.15687	1.01747

Table D-44 Performance Indicators for KY18 [TM≤5%]

Performance Indicator		(ID)	Unit
Total Length	571347.8	(All)	ft
Number of Segments	349		
Average length of segment	1637.1	(All)	ft
Max.Segment Length	66087.9	236	ft
Min.Segment Length	11.2	314	ft
Length/valve ratio	1215.6	(All)	ft/valve
Average number of valves per pipe	0.5	(All)	valve
Total number of valves	470	(All)	valve
Number of external valves	459	(All)	valve
Number of internal valves	11	(All)	valve
Max.Number of valves to be closed by segment	12	19	valve/segment
Min.Number of valves to be closed by segment	1	2	valve/segment
Average number of valves to be closed by segment	1.3	(All)	valve/segment
Total Demand	1664.4	(All)	GPM
Total Customers	11983.4	(All)	customer
Average demand loss/valve	1243.2	(All)	GPM/valve
Max.Demand loss/valve	322.2	AV-403	GPM/valve
Min.Demand loss/valve	89.3	AV-50	GPM/valve
Average customer loss/segment	45	(All)	customer/segment
Max.Customer loss/segment	541	76	customer/segment
Min.Customer loss/segment	0	1	customer/segment
Average Customer loss/valve	1243	(All)	customer/valve
Max.Customer loss/valve	2320	AV-403	customer/valve
Min.Customer loss/valve	643	AV-50	customer/valve

* For a customer, a household with 2.5 people on average and a daily demand per person of 80 gallons

Table D-45 Performance Metrics Summary for KY18 [TM≤5%]

	TM	PDND
Avg	0.38%(All)	0.46%(All)
Max	4.52% (s=76)	4.52%(s=76)
Min	0%(s=1)	0%(s=278)
StD	0.84%(All)	0.87%(All)

Table D-46 KY18 [TM≤5%] Statistics of the Top Ten Critical Segments (TM metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Sec. Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
76	6	13	4172.296	14	4	31	16840.63	32	46	448
96	3	4	92.129	5	0	0	0	0	5	467
68	8	22	7389.189	22	6	16	2209.033	22	44	462
63	3	13	9675.54	13	1	9	6121.448	8	21	443
225.1.2	3	3	61.489	4	4	6	853.635	10	14	465
106	8	19	4802.561	20	12	38	5483.837	50	70	455
256	6	9	2330.95	10	7	19	3953.634	26	36	451
58.2.2	11	29	8563.094	28	1	1	290.839	2	30	447
146.1	3	4	3623.117	5	0	0	0	0	5	466
201	5	30	7181.077	30	2	2	409.688	4	34	458

Table D-47 KY18 [TM≤5%] Statistics of the Top Ten Critical Segments (PDND metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
76	6	13	4172.3	14	4	31	16840.6	32	46	448
96	3	4	92.1	5	0	0	0	0	5	467
68	8	22	7389.2	22	6	16	2209.0	22	44	462
225.1.2	3	13	9675.5	13	1	9	6121.4	8	21	443
106	3	3	61.5	4	4	6	853.6	10	14	465
256	8	19	4802.6	20	12	38	5483.8	50	70	455
58.2.2	6	9	2331	10	7	19	3953.6	26	36	451
146.1	11	29	8563.2	28	1	1	290.8	2	30	447
201	3	4	3623.1	5	0	0	0	0	5	466
58.2.1	5	30	7181.1	30	2	2	409.7	4	34	458

Table D-48 KY18 [TM≤5%] Statistics for Top Ten Critical Valves

Valve ID	Valve INDEX	TM [%]	Total Primary Length [ft]	Total Secondary Length [ft]	Total Length [ft]	Merged Segments	
~AV-403	2182	0.193574	58883.05	168.878	58714.17	95	96
~AV-402	2181	0.153736	77297.96	31971.06	45326.89	96	302
~AV-165	1917	0.150747	47669.1	1089.487	46579.61	255	279
~AV-180	1934	0.150347	43931.91	3574.132	40357.78	251	146.2
~AV-136	1885	0.148528	51315.06	2342.045	48973.02	276	322
~AV-127	1875	0.148238	51792.76	4635.794	47156.96	86	308
~AV-130	1879	0.147222	51160.98	3327.856	47833.12	86	281
~AV-131	1880	0.146163	50856.27	1078.705	49777.56	277	280
~AV-132	1881	0.146142	50656.07	704.248	49951.82	271	279
~AV-176	1929	0.144979	45279.22	7986.006	37293.21	68	255

Table D-49 Topologic Metrics for KY18 [VN≤5%]

Topologic Metric		Link-Node	Arc-Node
Link Density	q	0.003098	0.007243
Average Node Degree	K	2.355	2.550
Diameter	D	97237.95	
Average Path Length	l	23988.27	
Spectral Radius	λ^{A}_{1}	3.193	3.977
Spectral Gap	$\Delta\lambda^{A}$	0.13084	0.19664
Algebraic Connectivity	λ^{L}_{2}	0.00149	0.00511
Eigengap	Δ^{L}	0.15687	1.00037

Table D-50 Performance Indicators for KY18 [VN≤10]

Performance Indicator		(ID)	Unit
Total Length	571347.8	(All)	ft
Number of Segments	353		
Average length of segment	1618.5	(All)	ft
Max.Segment Length	66087.9	236	ft
Min.Segment Length	11.2	314	ft
Length/valve ratio	1202.8	(All)	ft/valve
Average number of valves per pipe	0.5	(All)	valve
Total number of valves	475	(All)	valve
Number of external valves	467	(All)	valve
Number of internal valves	8	(All)	valve
Max.Number of valves to be closed by segment	9	19.1.1	valve/segment
Min.Number of valves to be closed by segment	1	2	valve/segment
Average number of valves to be closed by segment	1.3	(All)	valve/segment
Total Demand	1664.4	(All)	GPM
Total Customers	11983.4	(All)	customer
Average demand loss/valve	1833.4	(All)	GPM/valve
Max.Demand loss/valve	424.7	AV-403	GPM/valve
Min.Demand loss/valve	17.4	V5	GPM/valve
Average customer loss/segment	45	(All)	customer/segment
Max.Customer loss/segment	777	58.2	customer/segment
Min.Customer loss/segment	0	1	customer/segment
Average Customer loss/valve	1833	(All)	customer/valve
Max.Customer loss/valve	3058	AV-403	customer/valve
Min.Customer loss/valve	125	V5	customer/valve

* For a customer, a household with 2.5 people on average and a daily demand per person of 80 gallons

Table D-51 Performance Metrics Summary for KY18 [VN≤10]

	TM	PDND
Avg	0.38% (All)	0.46% (All)
Max	6.48% (s=58.2)	6.57% (s=58.2)
Min	0%(s=1)	0%(s=207)
StD	0.84%(All)	0.90%(All)

Table D-52 KY18 [VN≤10] Statistics of the Top Ten Critical Segments (TM metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
58.2	9	40	9524	40	9	21	4363	30	70	444
225	4	35	21938	33	6	14	3313	20	53	424
76	6	13	4172	14	4	31	16841	32	46	448
96	3	4	92	5	0	0	0	0	5	467
68	8	22	7389	22	6	16	2209	22	44	462
106	3	3	61	4	4	6	854	10	14	465
256	8	19	4803	20	12	38	5484	50	70	455
201	3	4	3623	5	0	0	0	0	5	466
12	3	3	690	4	0	0	0	0	4	466
58.1	9	34	17875	35	6	14	4584	20	55	433

Table D-53 KY18 [VN≤10] Statistics of the Top Ten Critical Segments (PDND metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
58.2	9	40	9524	40	9	21	4363	30	70	444
225	4	35	21938	33	6	14	3313	20	53	424
76	6	13	4172	14	4	31	16841	32	46	448
96	3	4	92	5	0	0	0	0	5	467
68	8	22	7389	22	6	16	2209	22	44	462
63	3	5	3437	6	2	18	66866	20	26	460
106	3	3	61	4	4	6	854	10	14	465
256	8	19	4803	20	12	38	5484	50	70	455
201	3	4	3623	5	0	0	0	0	5	466
12	3	3	690	4	0	0	0	0	4	466

Table D-54 KY18 [VN≤10] Statistics for Top Ten Critical Valves

Valve ID	Valve INDEX	TM [%]	Total Primary Length [ft]	Total Secondary Length [ft]	Total Length [ft]	Merged Segments	
~AV-403	2192	0.255199	71267.62	168.878	71098.74	92	91
~AV-402	2191	0.215361	89682.53	31971.06	57711.46	96	302
~AV-240	2011	0.205385	74626.25	1372.607	73253.64	211	213
~AV-376	2161	0.204734	131450.4	3538.727	127911.7	96	301
~AV-91	2310	0.201592	54380.91	1210.16	53170.75	11	336
~AV-90	2309	0.201387	53554.18	3769.704	49784.47	10	12
~AV-165	1927	0.200581	62041.19	1089.487	60951.7	255	279
~AV-244	2015	0.200379	75273.97	1783.148	73490.82	209	210
~AV-24	2010	0.199801	73770.32	7649.399	66120.92	68	212
~AV-243	2014	0.198032	74779.53	1398.267	73381.26	209	313

Table D-55 Topologic Metrics for KY18 [VN≤5]

Topologic Metric		Link-Node	Arc-Node
Link Density	q	0.003098	0.006471
Average Node Degree	K	2.355	2.543
Diameter	D	97237.95	
Average Path Length	l	23988.27	
Spectral Radius	λ^A_1	3.193	3.570
Spectral Gap	$\Delta\lambda^A$	0.13084	0.26336
Algebraic Connectivity	λ^L_2	0.00149	0.00416
Eigengap	Δ^L	0.15687	0.25631

Table D-56 Performance Indicators for KY18 [VN≤5]

Performance Indicator		(ID)	Unit
Total Length	571347.8	(All)	ft
Number of Segments	394		
Average length of segment	1450.1	(All)	ft
Max.Segment Length	66087.9	236	ft
Min.Segment Length	11.2	314	ft
Length/valve ratio	1105.1	(All)	ft/valve
Average number of valves per pipe	0.6	(All)	valve
Total number of valves	517	(All)	valve
Number of external valves	511	(All)	valve
Number of internal valves	6	(All)	valve
Max.Number of valves to be closed by segment	511	159.1.2.2.1.1	valve/segment
Min.Number of valves to be closed by segment	1	2	valve/segment
Average number of valves to be closed by segment	1.3	(All)	valve/segment
Total Demand	1664.4	(All)	GPM
Total Customers	11983.4	(All)	customer
Average demand loss/valve	583.6	(All)	GPM/valve
Max.Demand loss/valve	223.6	AV-403	GPM/valve
Min.Demand loss/valve	2.3	V47	GPM/valve
Average customer loss/segment	42	(All)	customer/segment
Max.Customer loss/segment	683	225	customer/segment
Min.Customer loss/segment	0	1	customer/segment
Average Customer loss/valve	584	(All)	customer/valve
Max.Customer loss/valve	1610	AV-403	customer/valve
Min.Customer loss/valve	17	V47	customer/valve

* For a customer, a household with 2.5 people on average and a daily demand per person of 80 gallons

Table D-57 Performance Metrics Summary for KY18 [VN≤5]

	TM	PDND
Avg	0.35%(All)	0.42%(All)
Max	5.70%(s=225)	5.70%(s=225)
Min	0%(s=1)	0%(s=207)
StD	0.70%(All)	0.76%(All)

Table D-58 KY18 [VN≤5] Statistics of the Top Ten Critical Segments (TM metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Secondary Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
225	4	35	21938	33	6	14	3313	20	53	424
96	3	4	92	5	0	0	0	0	5	467
106	3	3	61	4	4	6	854	10	14	465
68.2.2	5	6	2939	7	5	18	2018	23	30	465
76.1	4	5	1270	6	3	27	15641	27	33	449
201	3	4	3623	5	0	0	0	0	5	466
58.2.1	5	30	7181	30	2	2	410	4	34	458
12	3	3	690	4	0	0	0	0	4	466
58.1.1.1	5	11	5928	12	8	50	16597	58	70	444
63	3	5	3437	6	2	18	66866	20	26	460

Table D-59 KY18 [VN≤5] Statistics of the Top Ten Critical Segments (PDND metric)

Seg. ID	N. Valves	Primary Pipe Elements	Total Primary Length [ft]	Primary Isolated Nodes	N. Sec. Isolations	Sec. Pipe Elements	Total Secondary Length [ft]	Secondary Isolated Nodes	Total Isolated Nodes	Available Hydrants
225	4	35	21938	33	6	14	3313	20	53	424
96	3	4	92	5	0	0	0	0	5	467
63	3	5	3437	6	2	18	66866	20	26	460
106	3	3	61	4	4	6	854	10	14	465
68.2.2	5	6	2939	7	5	18	2018	23	30	465
201	3	4	3623	5	0	0	0	0	5	466
58.2.1	5	30	7181	30	2	2	410	4	34	458
76.1	4	5	1270	6	3	27	15641	27	33	449
12	3	3	690	4	0	0	0	0	4	466
58.1.1.1	5	11	5928	12	8	50	16597	58	70	444

Table D-60 KY18 [VN≤5] Statistics for Top Ten Critical Valves

Valve ID	Valve INDEX	TM [%]	Total Primary Length [ft]	Total Secondary Length [ft]	Total Length [ft]	Merged Segments	
~AV-403	2276	0.134365	43439.25	168.878	43270.37	95	96
~AV-154	1999	0.106575	40229.11	953.986	39275.12	255	312
~AV-143	1987	0.097986	40692.28	3150.652	37541.63	271	68.2.2
~AV-91	2394	0.094991	32860.13	1210.16	31649.97	11	336
~AV-256	2112	0.094887	46088.32	3719.687	42368.63	201	202
~AV-90	2393	0.094786	32033.4	3769.704	28263.7	10	12
~AV-402	2275	0.094526	61854.16	31971.06	29883.1	96	302
~AV-88	2390	0.093504	31214.86	1626.246	29588.61	7	12
~AV-181	2029	0.092971	31509.61	2475.928	29033.68	144.1.1	146.2.2
~AV-180	2028	0.092087	31115.86	2082.173	29033.68	251	146.2.2

APPENDIX E. BAR PLOTS FOR TEST NETWORKS WITH NEW VALVE CONFIGURATION

This section presents the bar plots reporting the results of the segment-based assessment for each of the test networks (KY6, KY8, and KY18) after the valve placement procedure has been applied. For the KY6 networks (TM_s≤5%,NV_s≤10,NV_s≤5) the following results are reported: (a) Topological Metric (TM), (b) Pressure Dependent Normal Demand (PDND) metric, (c) Pressure Dependent Fire Demand metric (PDFD) and (d) Pressure Dependent Hydrant Demand (PDHD) metric. For the KY8 and KY18 ((TM_s≤5%,NV_s≤10,NV_s≤5) the reported results include the Topological Metric (TM) and the Pressure Dependent Normal Demand (PDND) metric. Additionally the distribution of the valve layout is reported for each of the test networks, including the initial condition and final configuration for each objective

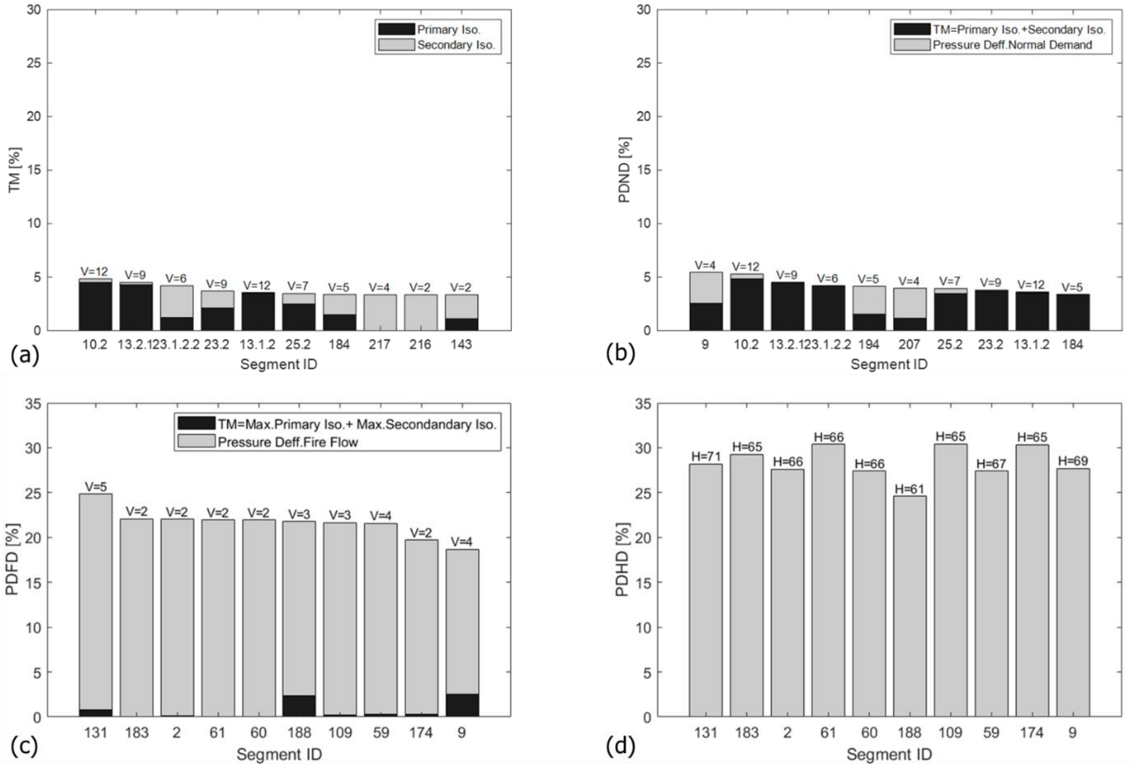

Figure E-1 KY6 (TM≤5%) Ten most critical segments for (a) Topological Metric (TM), (b) Pressure Dependent Normal Demand (PDND) metric, (c) Pressure Dependent Fire Demand metric (PDFD) and (d) Pressure Dependent Hydrant Demand (PDHD) metric Demand (PDHD) metric

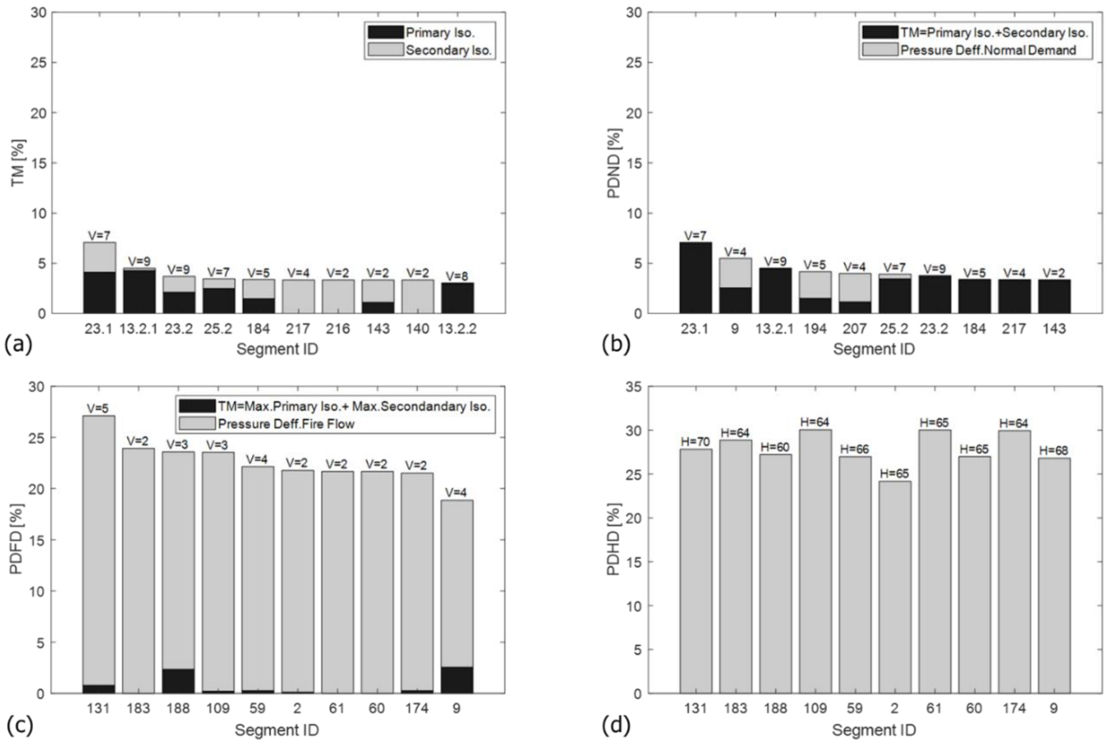

Figure E-2 KY6 (VN≤10) Ten most critical segments for (a) Topological Metric (TM), (b) Pressure Dependent Normal Demand (PDND) metric, (c) Pressure Dependent Fire Demand metric (PDFD) and (d) Pressure Dependent Hydrant Demand (PDHD) metric

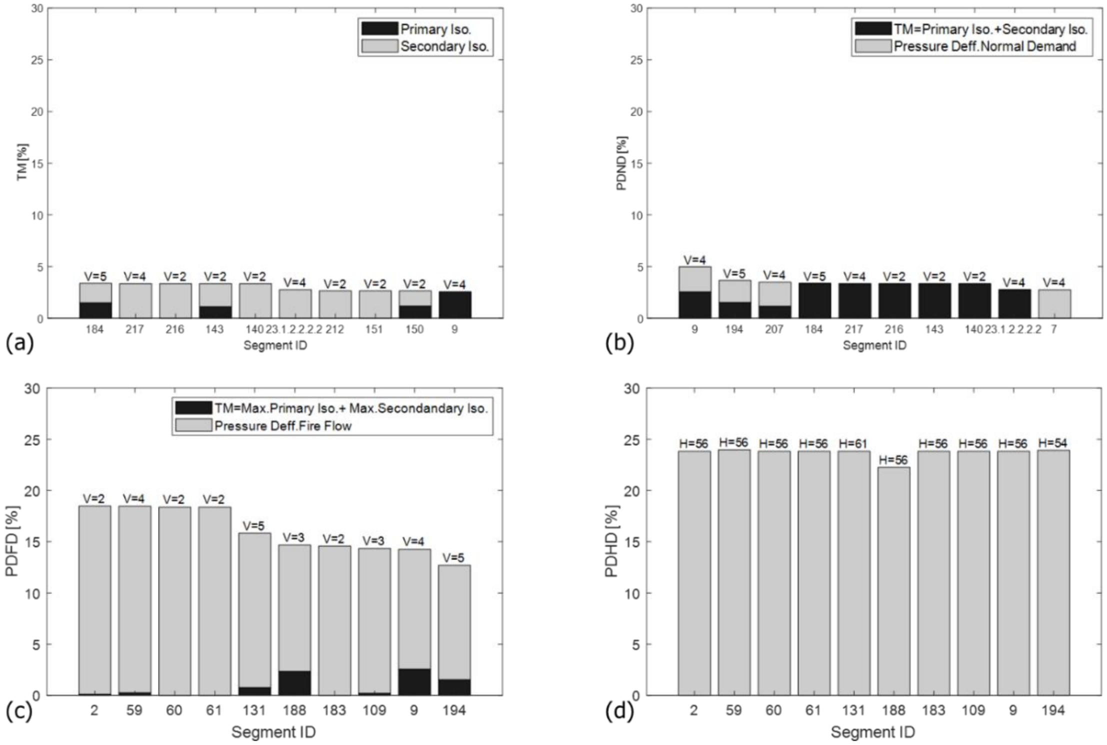

Figure E-3 KY6 (VN≤5) Ten most critical segments for (a) Topological Metric (TM), (b) Pressure Dependent Normal Demand (PDND) metric, (c) Pressure Dependent Fire Demand metric (PDFD) and (d) Pressure Dependent Hydrant Demand (PDHD) metric

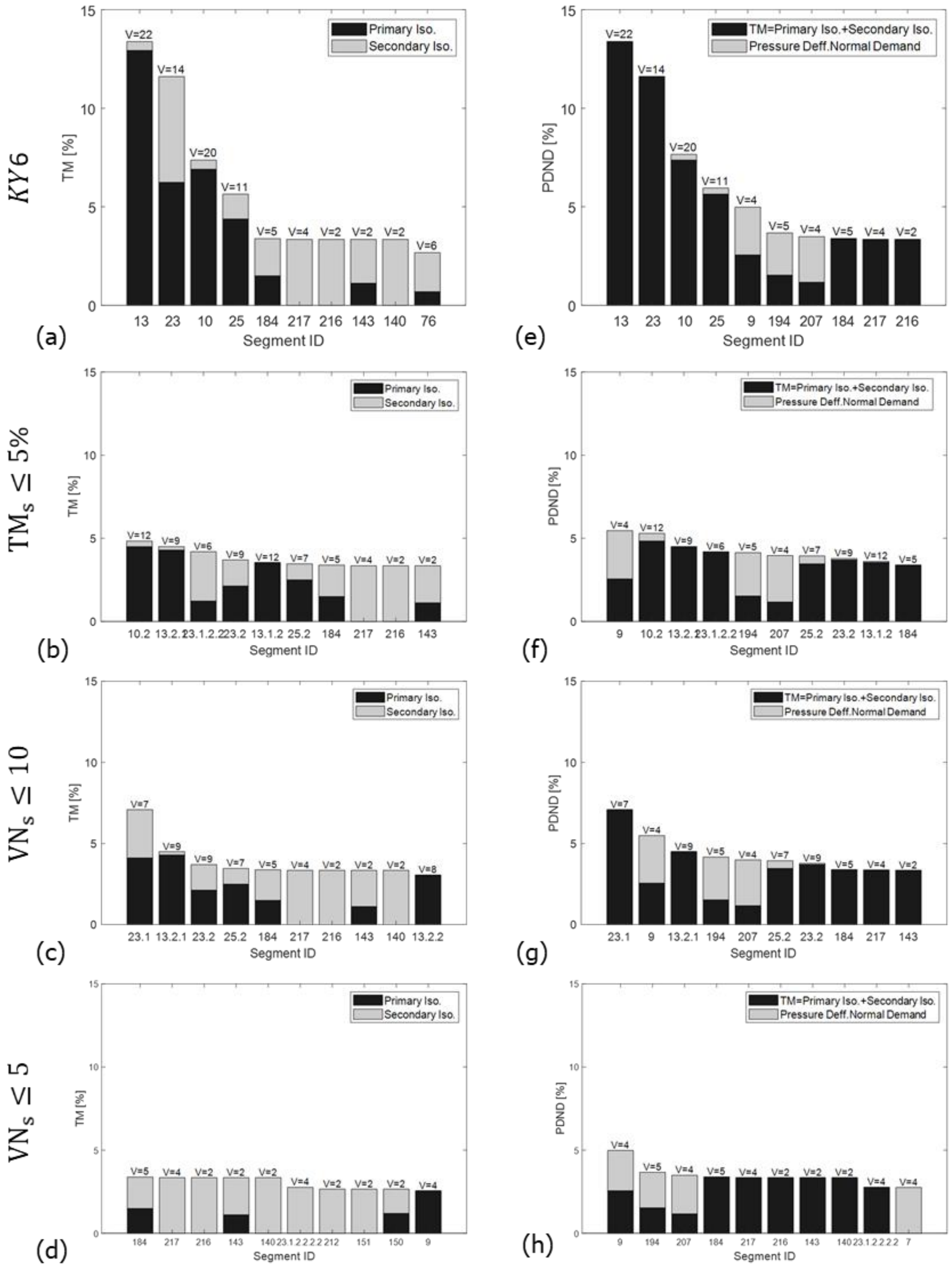

Figure E-4 (a-d)Top Ten Most Critical Topological Metric Results for KY6, and (e-h) Top Ten Most Critical Pressure Dependent Normal Demand Metric Results for KY6 with initial layout and after Valve Placement ($\mathrm{TM}_s \le 5\%, \mathrm{NV}_s \le 10, \mathrm{NV}_s \le 5$) Layout and after Valve Placement with objectives (b) TM≤5% ,(c) VN<10, and (d) VN<5

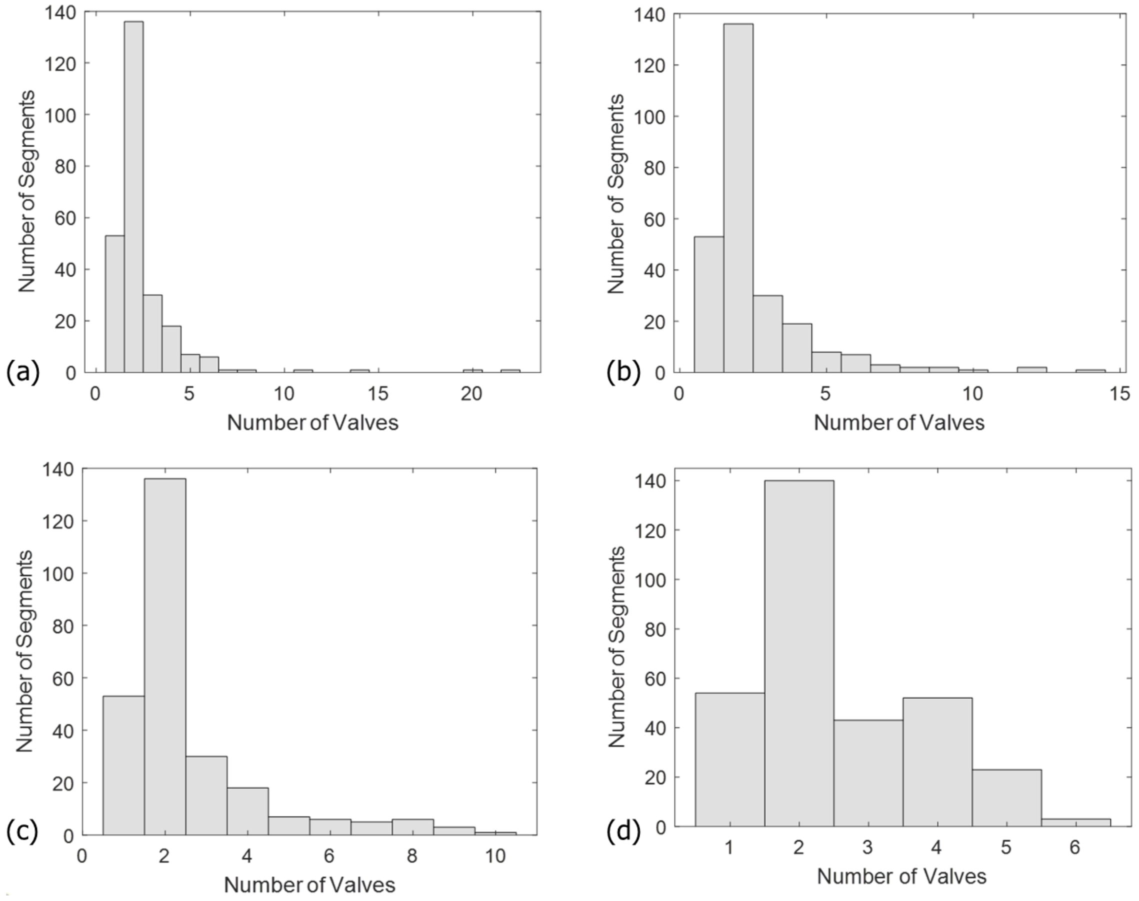

Figure E-5 Distribution of Valves Required per Segment for (a) Initial KY6 Valve Layout and after Valve Placement with objectives (b) TM≤5% ,(c) VN<10, and (d) VN<5

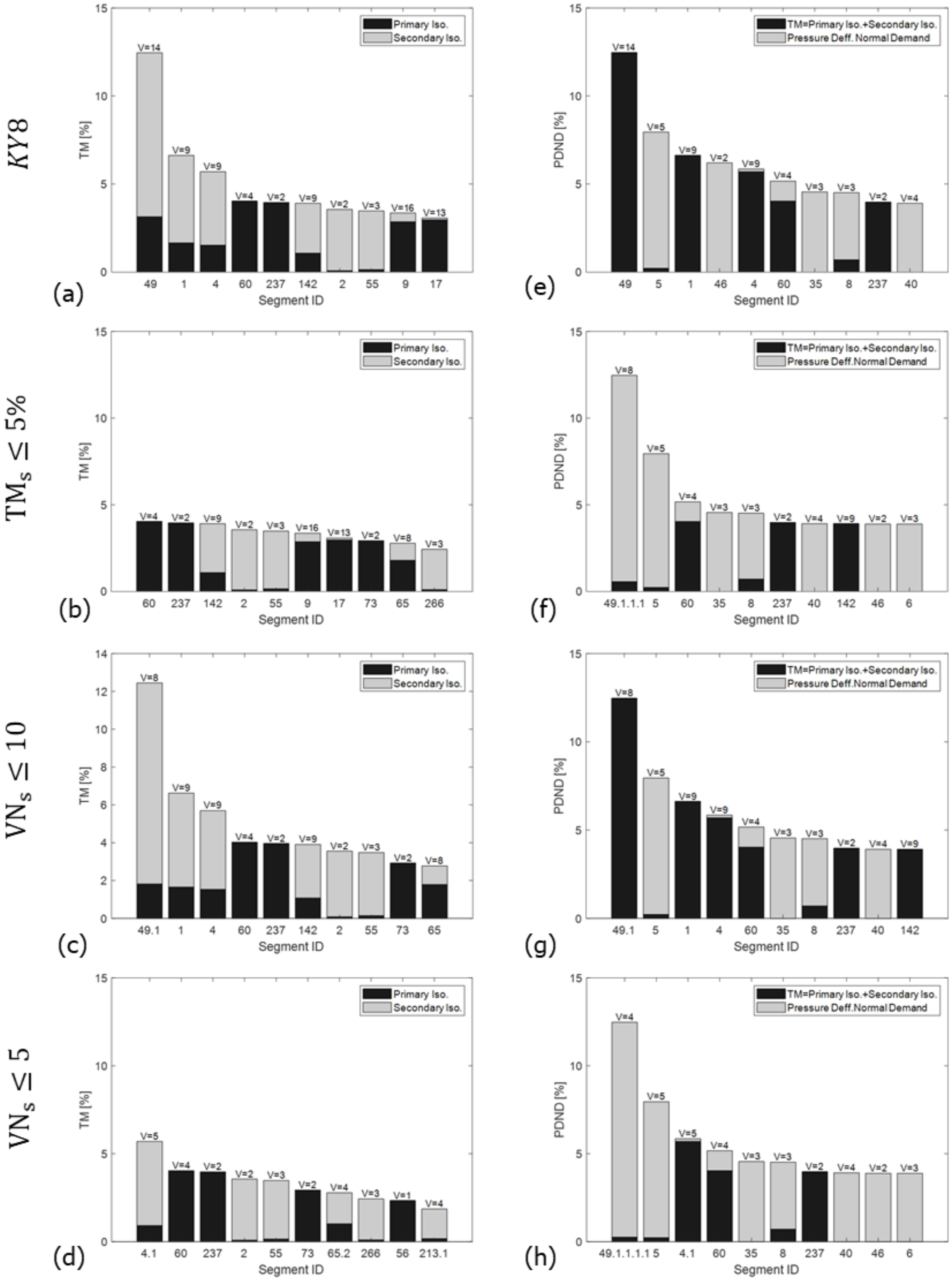

Figure E-6 (a-d)Top Ten Most Critical Topological Metric Results for KY8, and (e-h) Top Ten Most Critical Pressure Dependent Normal Demand Metric Results for KY8 with initial layout and after Valve Placement (TM_s≤5%,NV_s≤10,NV_s≤5)

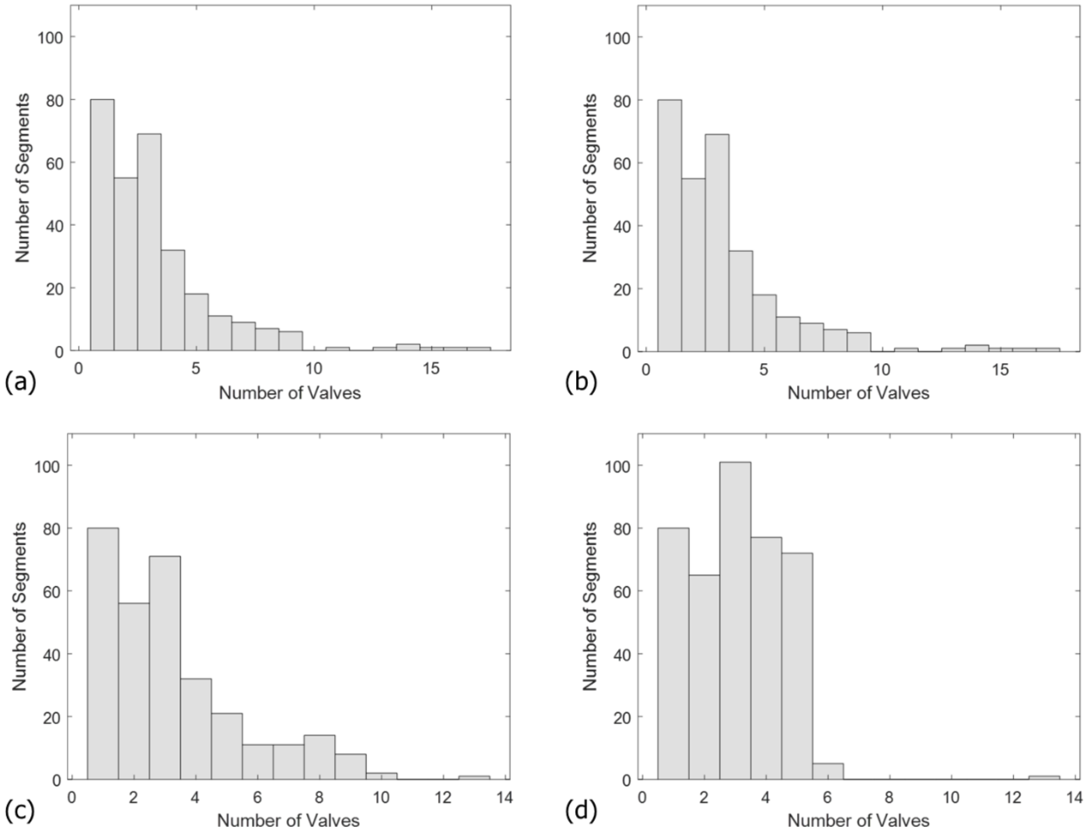

Figure E-7 Distribution of Valves Required per Segment for (a) Initial KY8 Valve Layout and after Valve Placement with objectives (b) TM≤5% ,(c) VN<10, and (d) VN<5

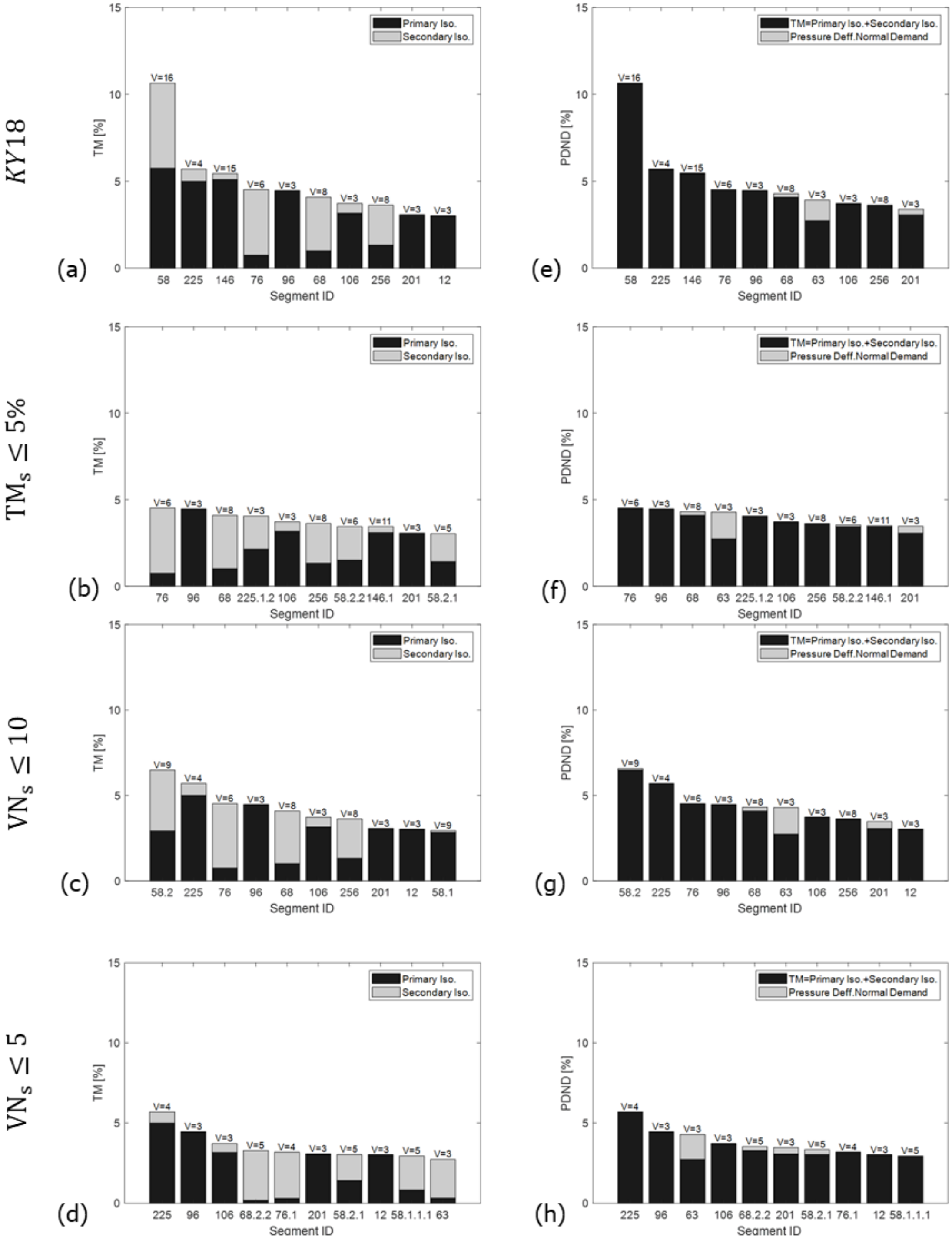

Figure E-8 (a-d)Top Ten Most Critical Topological Metric Results for KY18, and (e-h) Top Ten Most Critical Pressure Dependent Normal Demand Metric Results for KY18 with initial layout and after Valve Placement (TM_s≤5%,NV_s≤10,NV_s≤5)

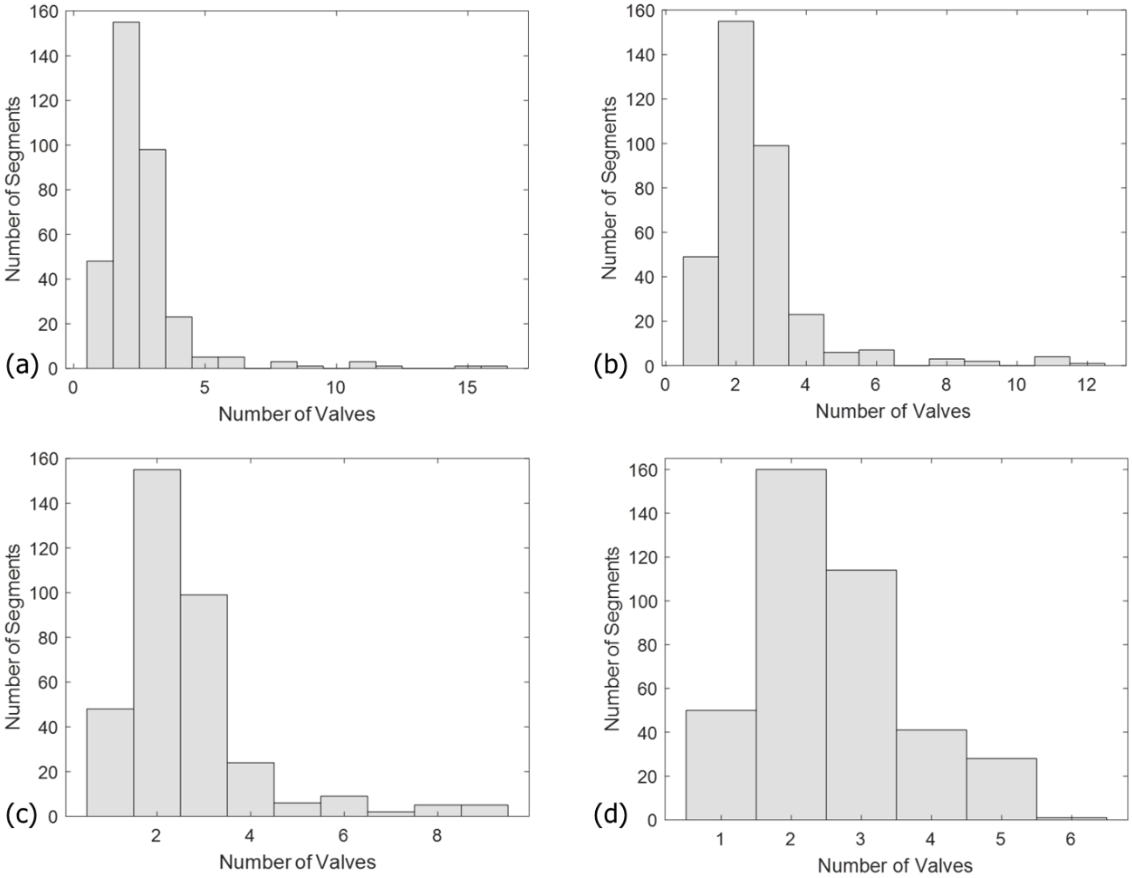

Figure E-9 Distribution of Valves Required per Segment for (a) Initial KY18 Valve Layout and after Valve Placement with objectives (b) TM≤5%, (c) VN<10, and (d) VN<5

APPENDIX F. CODE FLOWCHARTS

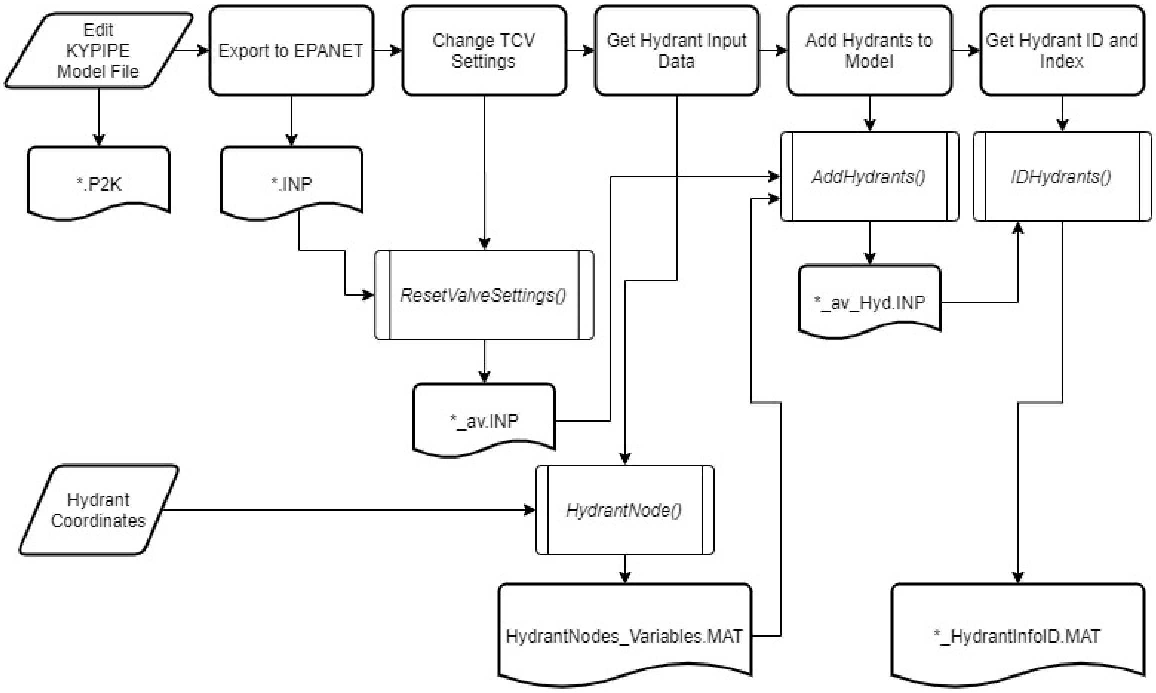

Figure F-1 Model File Configuration

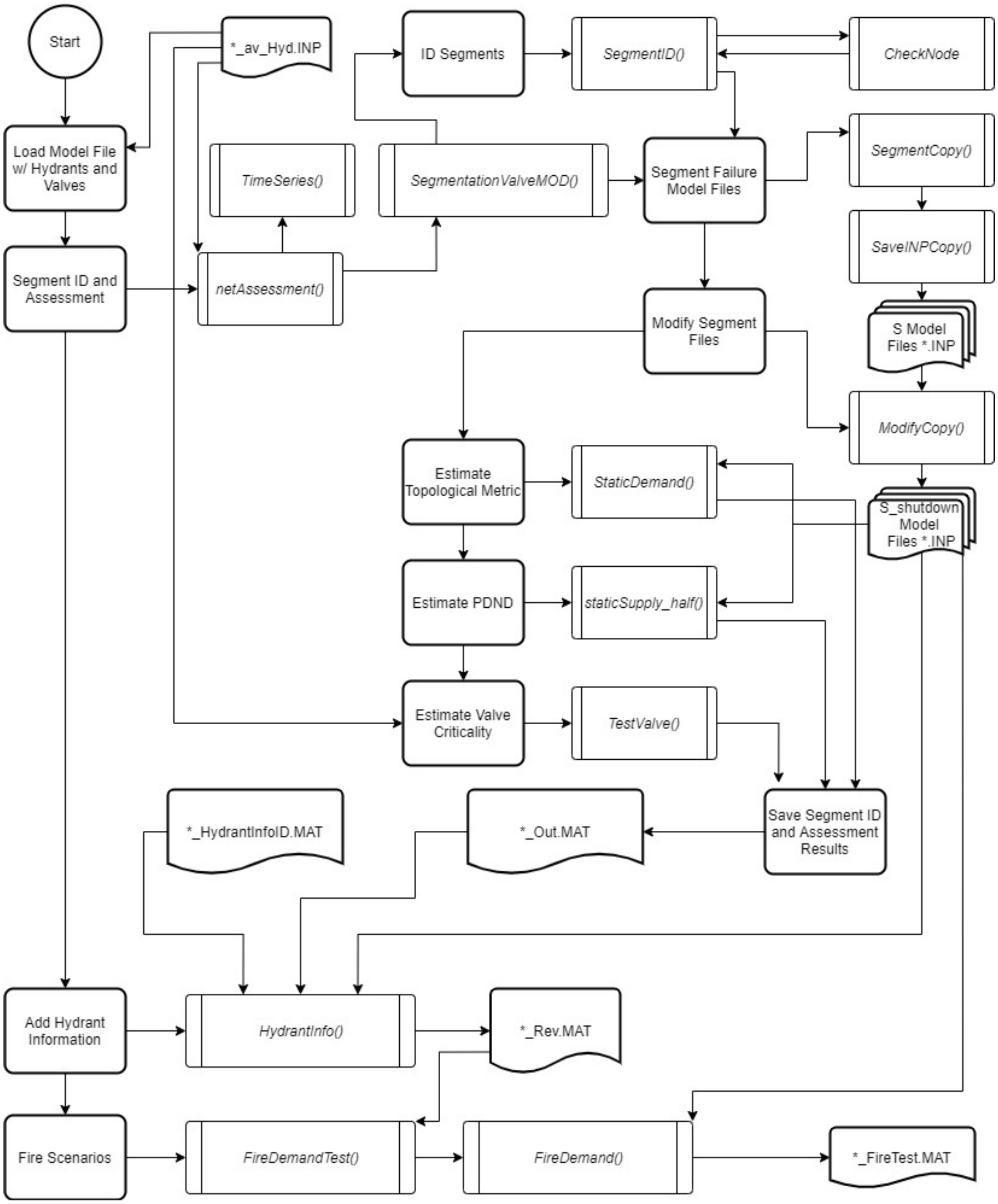

Figure F-2 Segment Identification and Segment Based Assessment Function Flowchart

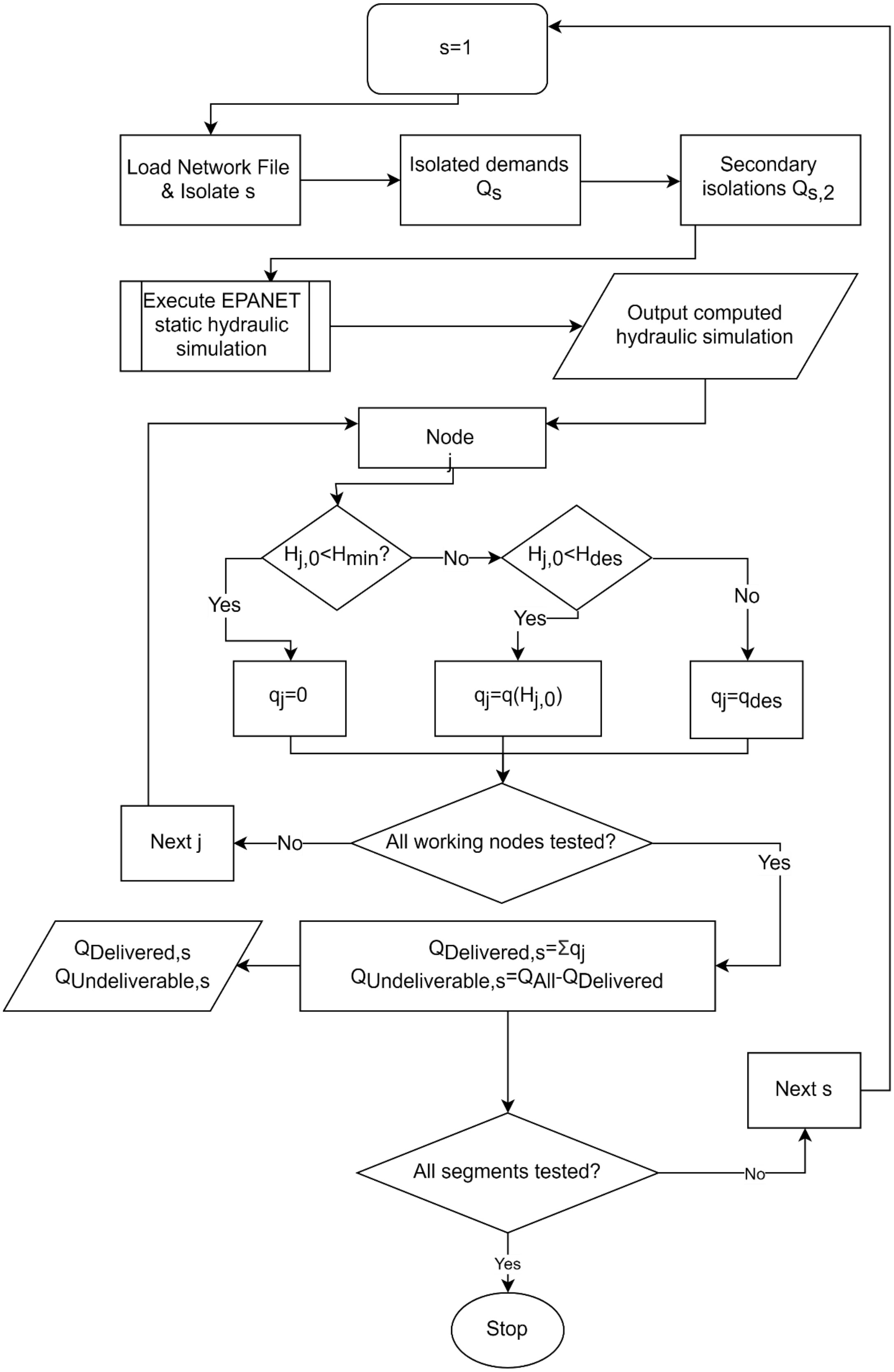

Figure F-3 Pressure Dependent Normal Demand Flowchart

Figure F-4 Fire Scenario Simulations Flowchart

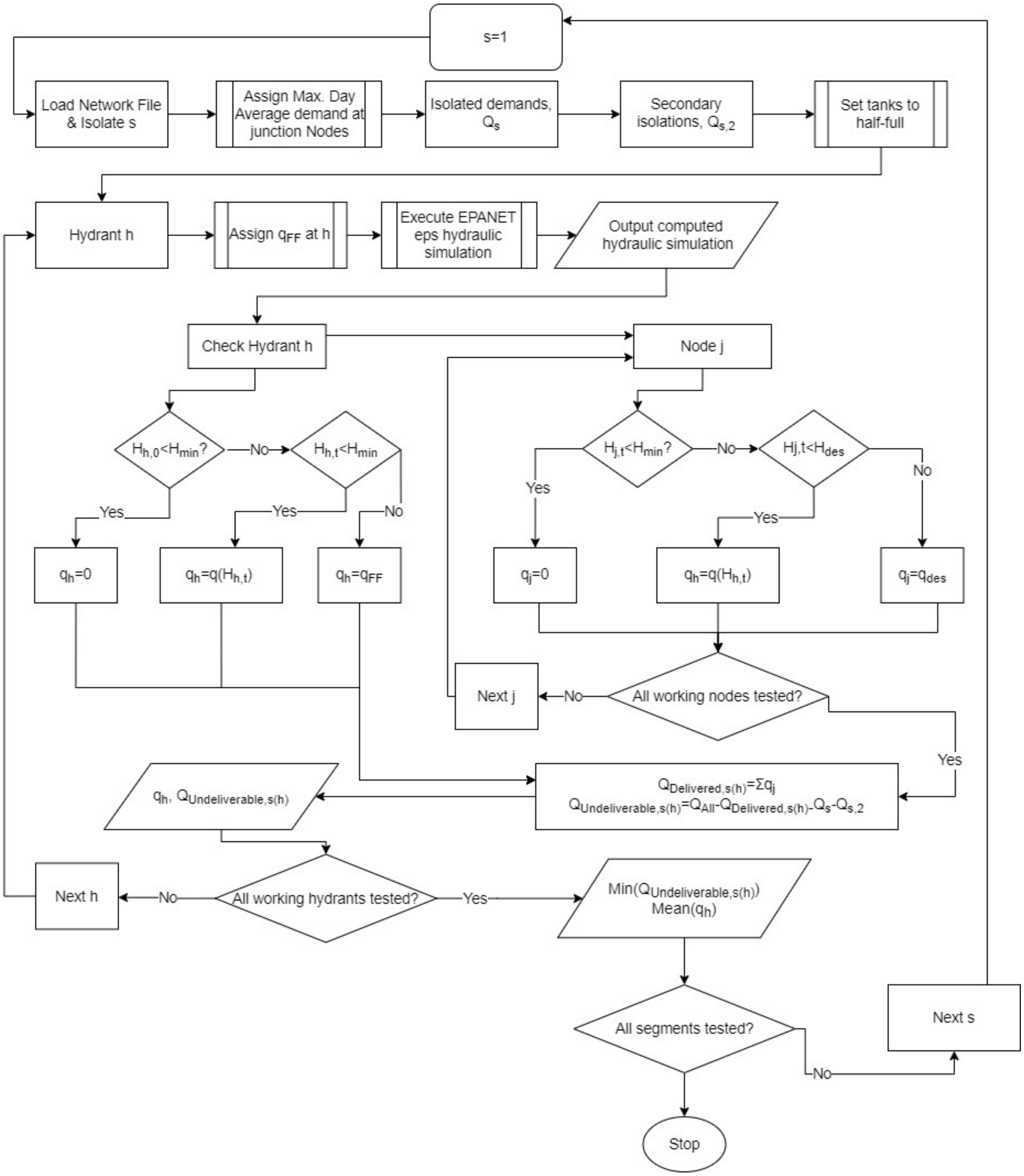

Figure F-5 Fire Scenario Simulations Flowchart

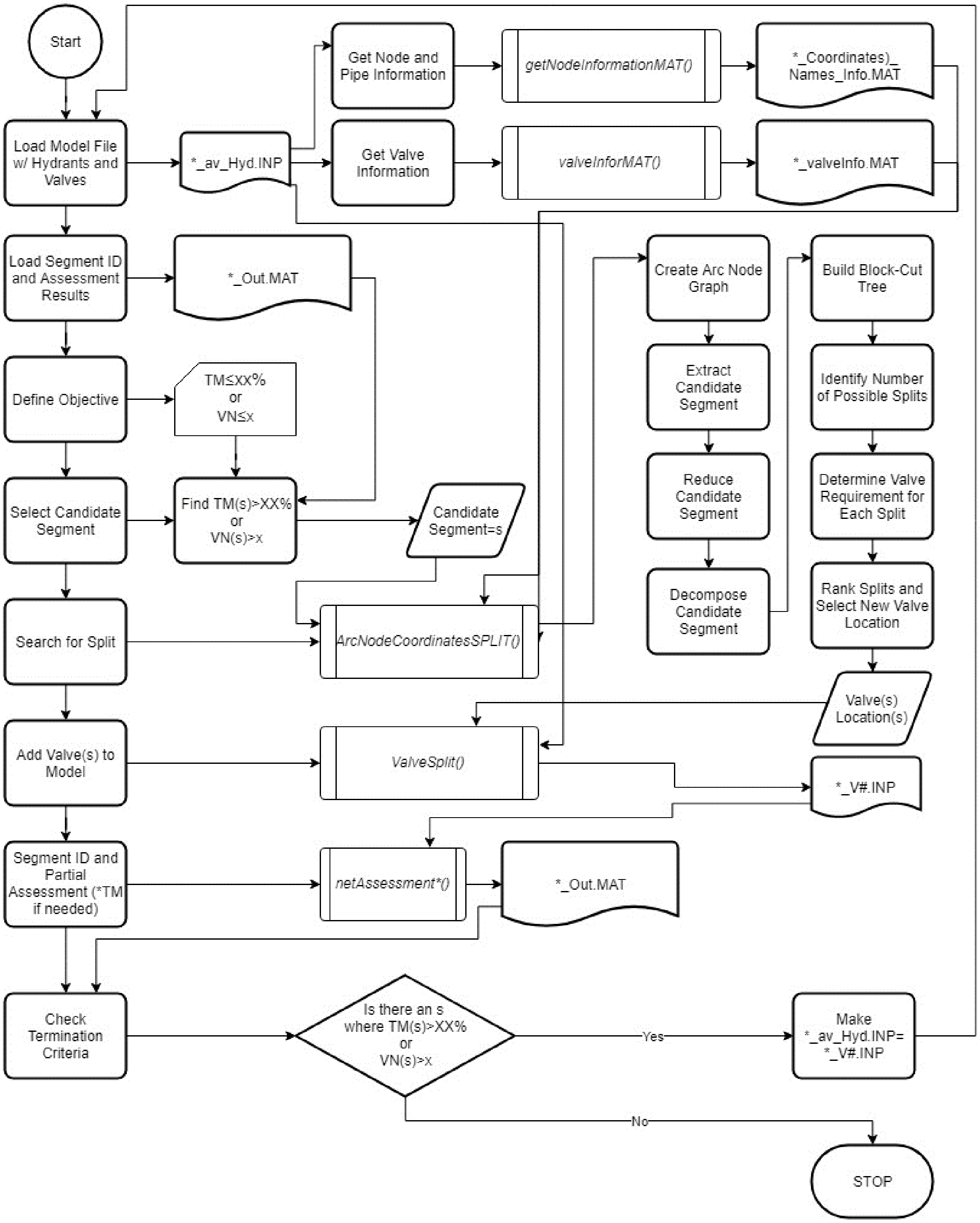

Figure F-6 Valve Placement Function Flowchart

APPENDIX G. MATLAB CODE

This section presents the functions and algorithms written in MATLAB used for the identification, assessment, and optimization. The functions are developed using the EPANET-MATLAB Toolkit (Eliades et al., 2016).

MATLAB® Code

Legend:
Blue Text = Comments
Black text = Variables, values, and operators
Orange text = Statement begin or end
Green text = Text

```
%% Routine for Segments to Split and Candidate Edges for Valve
Placement
%This routine uses the number of valves as a limit
%Created:06/16/20
%Last modified:06/26/20
%% Get node information
inpfn=*****;
[getNodeInformationMAT] = GetNodeInformationFUN(inpfn);

%%Type names of files if already known for start network
getNodeInformationMAT='Coordinates_Names_Info.mat';
networkOutputMAT=*****_av_Hyd.mat';
INPfilename='*****INPfileInfo.mat';
valveInfoMAT='*****_valveinfo.mat';
namefileMAT='*****_ValveOPTN5.mat';

%Change file name on CountValveFUN
%% Set Valve Number Limit
VN_limit=***;%Maximum allowed value of valves


%% Set list of segments to split
load(networkOutputMAT,'out2','out')

%% Get segment statistics
%%
ssegments=size(out2,2);
PrimaryDemandLoss=zeros(ssegments,1);

load(INPfilename,'basedemands_cell')

load(valveInfoMAT,'ExternalValveCount','nvalves')
basedemands=[basedemands_cell{1,1}];

cellDemands=basedemands_cell;
vDemands=[cellDemands{:}];
Nodes = {out2.Nodes}.';

for i=1:ssegments
    PrimaryDemandLoss(i)=sum(vDemands(Nodes{i}));
end

DayDemand=sum(vDemands);

demandLoss = [out.demandLoss].';
```

```
%% Topologic (from segAssessment)
pTopologyMetric=[out.PercentageLoss].';
ExtValve=ExternalValveCount;


ResultID=cell(numel(SplitSegList),3);

VNcheck=0;
i=0;
m=0;
inpname='*****';%Change name and in split function
IDHydrantMAT='******_HydInfo.mat';%Hydrant information file
ogLinksL=[out2.LinksL].';

while VNcheck<1
    [CritVN,CritID_V]=max(ExtValve);
    if CritVN>VN_limit

        SplitSegList=CritID_V;
        m=m+1; %Update counter for number of splits

        CritIDsplit_V(m)=CritID_V;
        Critsplit_V(m)=CritVN;


        Split=CritID_V;
        disp('Start search for split')
        [EdgeID1,JunctionID1,JunctionID2] =
ArcNodeCoordinatesSPLIT2(networkOutputMAT,getNodeInformationMAT,Split);
        ResultID{m,1}=JunctionID1;
        ResultID{m,2}=JunctionID2;
        ResultID{m,3}=EdgeID1;
        disp('Elements for split returned')
        if numel([EdgeID1{:}])>0
            for k=1:numel(EdgeID1)
                i=i+1; %Update counter for number of split
                %Split Network
                disp('Start split function')
                j=num2str(i);
                ValveID=['V', j];

                [newinpname_valve] = ValveSplit2(inpname,
EdgeID1{k}{:},ValveID);%Removed {:} at EdgeID1
                inpname=erase(newinpname_valve,'.inp');
            end
            %Run new TM assessment
            newfilename=erase(newinpname_valve,'.inp');

            disp('Start assessment')
            [out,out2,valveList,valveAdjacent,OutList] =
segAssessmentSIMP(newfilename);

            [filename_COORD] = NodeInfo_COORD(newfilename);
            getNodeInformationMAT=filename_COORD;

            networkOutputMAT=[newfilename,'.mat'];
```

```
AddHydrantInfo_seg2(newfilename,networkOutputMAT,IDHydrantMAT)
            INPfilename=[newfilename,'INPfileInfo.mat'];

            %Count valves
            [filenameValveInfo] = CountValveFUN(newfilename,out2);

            %load valve total
            load(filenameValveInfo,'nvalves','ExternalValveCount')
            ExtValve=ExternalValveCount;

            nEdgeIDs=numel(EdgeID1);
            segmentIDs_Split{m,1}=valveList{[1:nEdgeIDs],2};
            segmentIDs_Split{m,2}=valveList{[1:nEdgeIDs],4};

            %Get link length
            newLinksL=[out2.LinksL].';
            nsegments=size(out2,2);
            segmentIDs=zeros(nsegments,1);

            %Compare SegmentIDs
            for k=1:numel(newLinksL)
                searchIDs=find(ogLinksL==newLinksL(k));
                if numel(searchIDs)>0
                    segmentIDs(k)=find(ogLinksL==newLinksL(k));
                else
                    segmentIDs(k)=0;
                end
            end

            segmentIDs_Split{m,3}=segmentIDs; %Save IDs

            ogLinksL=newLinksL;

            inpname = newfilename;
            [CritVN,CritID_V]=max(ExtValve);

        else
            disp(['ID:',num2str(CritID_V),' possible bridge']);
            ExtValve(CritID_V)=0;

            segmentIDs_Split{m,1}=[];
            segmentIDs_Split{m,2}=[];
            segmentIDs_Split{m,3}=[];
        end
    else
        %Condition has been met exit while loop and save results
        disp('User limiting threshold met')
        VNcheck=1;

    end

end

save(namefileMAT);
```

```
function [filename] = GetNodeInformationFUN(inpfn)
%GetNodeInformationFUN Retrieves file information used on
%ArcNodeCoordinates (function and script)
% Loads EPANET file and retrieves element information to avoid loading
the
% toolkit multiple times on the other functions
% Created:06/16/2020
% Last Modified:06/16/20
%% Get node information
%%
%Load Epanet fie
d=epanet(inpfn);

%Get all node coordinates
AllCoordinates=d.getNodeCoordinates;
%Get link names
LinkName=d.getLinkNameID;
%Get node names
NodeName=d.getNodeNameID;
%Retrieves the id of the from/to nodes of all links
NodestoLink=d.getNodesConnectingLinksID;
%Retrieves the index of the from/to nodes of all links
LinkNodeIDX=d.getLinkNodesIndex;
%Retrieve base demands
BaseDemands=d.getNodeBaseDemands;
%Retrieve Node Type Index
NodeType=d.getNodeTypeIndex;
%Build Connectivity Matrix
ConnectivityMatrix_file=d.getConnectivityMatrix;
%Unload Epanet file
d.unload;

%Save variables for later use
filename='Coordinates_Names_Info.mat';
save(filename,'AllCoordinates','LinkName','NodeName','NodestoLink','Lin
kNodeIDX','BaseDemands','NodeType','ConnectivityMatrix_file');
fclose('all');
end
```

```
function [EdgeID1, JunctionID1,JunctionID2] =
ArcNodeCoordinatesSPLIT2(networkOutputMAT,getNodeInformationMAT,Split)
%ArcNodeCoordinatesSPLIT Determined edge and respective junction nodes
%where a valve can be placed for a given segment split (Split=Segment
ID)

%   Function Based on the ArcNodeCoordinates script. It creates a graph
for
%   the initial network, based on the segment selected as candidate to
%   split.
%   Graphing can be commented out to reduce computing time.

% Created:06/16/2020
% Last Modified:06/26/20
%% Load MATLAB results
load(networkOutputMAT,'out2','valveList'); %Load results file
```

```
boundary1 = {out2.boundary}.';%Extract boundary array
load(getNodeInformationMAT)%Load coordinate information,see script
(GetNodeInformation)

nvalves=size(valveList,1);
valvetosegment={valveList{:,2}}';

fromSegment=zeros(nvalves,1);
toSegment=zeros(nvalves,1);

for i=1:nvalves
    ncolumns=numel(valvetosegment{i,1});
    if ncolumns==2
        fromSegment(i)=valvetosegment{i,1}(1);
        toSegment(i)=valvetosegment{i,1}(2);
    else
        fromSegment(i)=valvetosegment{i,1}(1);
        toSegment(i)=valvetosegment{i,1}(1);
    end
end

G=graph(fromSegment,toSegment);
%% Figure
% figure
% % subplot(2,2,1)
% plot(G);

%% Identify duplicate valve links
boundary1;

valveIndex = {out2.valveIndex}.';

nSegments=size(boundary1,1);
duplicatevalves=cell(nSegments,1);

for i=1:nSegments
    nboundary=numel(boundary1{i,1});
    for j=1:nboundary
        nfinds=numel(find([valveIndex{i,1}]==valveIndex{i,1}(j)));
        if nfinds>1

duplicatevalves{i,1}=[duplicatevalves{i,1},valveIndex{i,1}(j)];
            duplicatevalves{i,1}=unique(duplicatevalves{i,1});
        end
    end
end

boundary1copy = boundary1;

for i=1:nSegments
    nduplicates=numel(duplicatevalves{i,1});
    if nduplicates>0
        for j=1:nduplicates
            duplicateNodes=LinkNodeIDX(duplicatevalves{i,1}(j),:);

boundary1copy{i,1}=setdiff([boundary1copy{i,1}],duplicateNodes);
        end
```

```
    end
end

%% Get Polygon coordinates
valveIndexcopy = {out2.valveIndex}.';
nSegments=size(valveIndex);

allX=[AllCoordinates{1,1}];
allY=[AllCoordinates{1,2}];

xvertex={};
yvertex={};

for i=1:nSegments

    xvertex{i}=[allX(boundary1copy{i})]';
    yvertex{i}=[allY(boundary1copy{i})]';

    nvertex=numel(boundary1copy{i});

    if nvertex<3

        centX(i)=xvertex{i}(1);
        centY(i)=yvertex{i}(1);

    else
        P=[xvertex{i};yvertex{i}]';
        pgon=polyshape(P,'Simplify',true);
        % %         [X_b,Y_b]=boundary(pgon);
        % %         pgon=polyshape(X_b, Y_b);
        [X,Y]=centroid(pgon);
        centX(i)=X;
        centY(i)=Y;

    end


end
%% Figure
% figure
subplot(2,2,1)
plot(G,'XData',centX,'YData',centY);

%%
%Get connectivity matrix and weights from GetNodeInformation.m script

%Get Node IDX by segment
NodesbySegment = {out2.Nodes}.';
%Get boundary nodes IDX by segment
BoundaryNodesbySegment={out2.boundary}.';
%Get hydrant nodes IDX by segment
NodesHyd={out2.NodesHyd}.';
%Get end nodes IDX
NodesEnd={out2.End}.';

%% Select segment to split by used prompt
%Select segment candidate
```

```
% prompt = 'Which segment should be tested for split?: ';
% Split = input(prompt);

%%
SplitNodes=[NodesbySegment{Split,1}];
SplitBoundaries=[BoundaryNodesbySegment{Split,1}];
SplitHyd=[NodesHyd{Split,1}];

TankNode=find(NodeType==2);
ResNode=find(NodeType==1);

SplitFinal=setdiff(SplitNodes,SplitBoundaries);
SplitFinal=setdiff(SplitFinal,SplitHyd);
%Remove sources if any
SplitFinal=setdiff(SplitFinal,TankNode);
SplitFinal=setdiff(SplitFinal,ResNode);
BaseDemandsM=[BaseDemands{1,:}];
SplitBD=BaseDemandsM(SplitFinal);

A=ConnectivityMatrix_file;
A=A(SplitFinal,:);
A=A(:,SplitFinal);

splitX=allX(SplitFinal);
splitY=allY(SplitFinal);

splitNames={NodeName{1,SplitFinal}};

%Check if there are enough viable elements to make a split, the script
will
%stop here if not enough elements exist
if numel(SplitFinal)<2
    disp('Not enough elements in this segment for new split')
    EdgeID1{1,1}=[];
    JunctionID1{1,1}=[];
    JunctionID2{1,1}=[];
    return
end
%%
GSplit = graph(A~=0);
GSplit.Nodes.Name=splitNames';
% GSplit.Nodes

%% Figure
% figure
subplot(2,2,2)
psplit=plot(GSplit,'XData',splitX,'YData',splitY);
%%
%BiConnectedComponent bins and cut nodes
[edgebins,iC] = biconncomp(GSplit);

%Highlight cut nodes
highlight(psplit,iC);

%BiconnectedComponent tree
[tree,ind] = bctree(GSplit);
```

```
%% New figure highlight biconnectedcomponents
% figure
subplot(2,2,3)
psplit2=plot(GSplit,'XData',splitX,'YData',splitY,'LineWidth',2);
%%
psplit2.EdgeCData =  biconncomp(GSplit);

%Tree cut nodes
%Index indicating the component represented by node i. The value is
zero if node i represents a cut vertex.
treeCut=find(tree.Nodes.ComponentIndex==0);

%% Graph tree
% figure
subplot(2,2,4)
p2 = plot(tree,'MarkerSize',9);
highlight(p2,treeCut,'Marker','d','NodeColor','r')
%%

%Group lumped demands of nodes into tree nodes
nTreeNodes=numel(unique(ind)); %Only nodes in tree that map out to
nodes in GSplit
uniqueTreeNodes=unique(ind);
ntreeTotal=size(tree.Nodes,1);
treeDemands=zeros(1,ntreeTotal);

GnodesTree=[];

for i=1:nTreeNodes
    k=uniqueTreeNodes(i);%Tree node examined
    GSplitNodes=find(ind==uniqueTreeNodes(i)); %Find nodes from GSplit
that are lumped in each tree node
    treeDemands(k)=sum(SplitBD(GSplitNodes));%Assigned to tree node
examined, those nodes that don't map out to nodes in G are zero
    GnodesTree{k}=GSplitNodes; %Nodes from G that are included in node
k or uniqueTreeNode(i) of tree
end

%Check if there are several locations available for valve locations,
unlike
%the previous check this might mean that there us only one viable valve
%location

if nTreeNodes<2
    disp('Not enough locations, use the location available')

    if nTreeNodes==1
        disp('No cut points available (single tree node), skip and find
alternative modification')
        EdgeID1{1,1}=[];
        JunctionID1{1,1}=[];
        JunctionID2{1,1}=[];
        return
    end

    checkedges=numedges(GSplit);
    if numel(checkedges)==1
```

```
        disp('Use the single edge available to place valve')
    end

    splitNames;

    IDXgraphedge=findedge(GSplit,splitNames(1),splitNames(2));
    [sOut,tOut] = findedge(GSplit,IDXgraphedge);%Retrieves edge index
number of in the GSplit graph

    idxsOut=SplitFinal(sOut);
    idxtOut=SplitFinal(tOut);

    [findsOut,~]=find(LinkNodeIDX==idxsOut);
    [findtOut,~]=find(LinkNodeIDX==idxtOut);

    linkIDXsearch=intersect(findsOut,findtOut);
    EdgeID1{1,1}=LinkName(linkIDXsearch);
    JunctionID1{1,1}=NodeName(idxsOut);
    JunctionID2{1,1}=NodeName(idxtOut);

    return
end


%Get tree edges connected nodes
treeLines=tree.Edges;
treeLinesMatrix=[treeLines{:,:}];

nCuts=numel(treeCut);
removedTreeEdges=[];

branch1=[];
branch2=[];

demand1=[];
demand2=[];

DIFFdemand=[];

idxcuts=[];

otherTreenode=[];
otherGnode=[];
EXPotherGnode=[];

for i=1:nCuts
    treeRed=tree;
    [row, col]=find(treeLinesMatrix==treeCut(i));
    removedTreeEdges{i}=row;
    nRemove=numel(row);


    idxcuts(i)=find(ind==treeCut(i));%Node index in G from the node
index in cut tree


    for j=1:nRemove
```

```
        treeRed2=rmedge(treeRed,row(j));%Remove tree edge incident to
cut node
        othernode=treeLinesMatrix(row(j),:);
        othernode=setdiff(othernode,treeCut(i));%Other tree node that
is not cut node

        otherTreenode{i,j}=othernode;
        otherGnode{i,j}=GnodesTree{othernode}; %Nodes from G that are
included in othernode from tree

        if size(GnodesTree{othernode})<1
            [row2, col2]=find(treeLinesMatrix==othernode);

EXPothernode=setdiff(treeLinesMatrix(row2,:),treeCut(i));%Find the
other connected cut node, this node doesn't map out to G elements
            EXPothernode=unique(setdiff(EXPothernode,othernode));
            EXPotherTreenode{i,j}=EXPothernode;
            EXPotherGnode{i,j}=GnodesTree{EXPothernode};
        else
            EXPotherGnode{i,j}=GnodesTree{othernode};
            EXPotherTreenode{i,j}=othernode;
        end


branch1{i,j}=dfsearch(treeRed2,treeLinesMatrix(row(j),1));%Examine each
side of removed edge
        branch2{i,j}=dfsearch(treeRed2,treeLinesMatrix(row(j),2));

        demand1{i,j}=sum(treeDemands(branch1{i,j}));
        demand2{i,j}=sum(treeDemands(branch2{i,j}));

        %Matrix for difference in demands, used later to define most
        %"effective" split point
        DIFFdemand{i,j}=abs(demand1{i,j}-demand2{i,j});

    end

end

% Convert from cell to matrix differences
DIFFdemand( cellfun('isempty',DIFFdemand) ) = {sum(SplitBD)};
matDIFFdemand=cell2mat(DIFFdemand);
matDIFFdemand=matDIFFdemand./sum(SplitBD); %normalize by demand,
previous empty spots will take a value of 1


% Define how nodes in G match in bins
binnodesTree=[];
for i=1:nTreeNodes
    k=uniqueTreeNodes(i);%Tree node examined
    nodeschecked=GnodesTree{k}; %Cut nodes will "belong" to different
bins
    %     nodeschecked=setdiff(GnodesTree{k},idxcuts); %Remove cut
nodes, the edges will belong to different bins
    nGnodes=numel(nodeschecked); %Nodes from G that are included in
node k or uniqueTreeNode(i) of tree
    tempedgelist=[];
```

```
    for j=1:nGnodes
        tempedgelist=[tempedgelist, outedges(GSplit,nodeschecked(j))'];
    end
    binnodesTree{k}=unique(edgebins(tempedgelist)); %Bin nodes
contained in the tree nodes, cut nodes "belong" to several bins
simultaneously so they are excluded

end

%Define the number of valves that would be required for each cut point

valvesreq=[];
binsvalvesreq=[];
valvesedgereq=[];

for i=1:nCuts
    incidentEdge=[];
    incidentbins=[];
    uniquebins=[];

    cutnode=idxcuts(i);
    incidentEdge=outedges(GSplit,cutnode);
    incidentbins=edgebins(incidentEdge);%go from incident edges to
incident bins
    uniquebins=unique(incidentbins);%list the unique bins that are
incident
    nbins=numel(unique(incidentbins));%number of bins that are incident
to cut node

    for j=1:nbins
        valvesreq{i,j}=numel(find(incidentbins==uniquebins(j)));%Number
of incident edges for a given bin
        binsvalvesreq{i,j}=uniquebins(j); %Bins for edges for valve
count
        valvesedgereq{i,j}=incidentEdge(incidentbins==uniquebins(j));
    end
end

% From possible splits define the most "even" split with the least
number
% of valves required
% The scrip will continue to look for a location that provides a viable
% location for a single valve
ogmatDIFFdemand=matDIFFdemand;
%Find the minimum values (most even split)
[M1,I1] = min(matDIFFdemand,[],2); %check minimum value by row
[M2,I2] = min(M1); %Check wich row has the minimum value. Considers
only one value even if the minimal value appears multiple times in the
array
% % Address with minimum value
% matDIFFdemand(I2,I1(I2));

ogI1=I1;
ogI2=I2;

%Cut nodes
treeCut(I2);%Tree Cut Node
```

```
idxcuts(I2);%G cut node

%Edges Removed
removedTreeEdges{1,I2}(I1(I2),1); %Removed tree edge for current demand
split

%Nodes on other end
otherGnodesearch=EXPotherGnode{I2,I1(I2)};
otherTreenodesearch=EXPotherTreenode{I2,I1(I2)};

%Bin or bins for other tree node
binsearch=[binnodesTree{1,otherTreenodesearch}];

%What if there is more than one bin? Reduce it to shared bin, if it is
more
%than one it is likely to be also a cut node
nbinsearch=numel(binsearch);
if nbinsearch>1
    binsearch=intersect(binsearch,[binnodesTree{1,(treeCut(I2))}]);
end

%Get information on possible valve location, define candidate link and
end
%nodes
idxsearch=find([binsvalvesreq{I2,:}]==binsearch);
nvalvessearch=valvesreq{I2,idxsearch};
% valvesedgereq{I2,idxsearch};
disp(['Valves required from search: ',num2str(nvalvessearch)])

% Check if the number of valves exceeds the single valve requirement
if nvalvessearch>1
    disp('More than one valve needed look for alternative')

    % Rewrite Address with minimum value and do a new search
    matDIFFdemand(I2,I1(I2))=1;
    minSplitRequired=0.5; %Change this by user preference
    splitoptions=find(matDIFFdemand<minSplitRequired);

    for k=1:numel(splitoptions)
        %Find the minimum values (most even split) with modified
entries

        [M1,I1] = min(matDIFFdemand,[],2); %check minimum value by row
        [M2,I2] = min(M1); %Check wich row has the minimum value.
Considers only one value even if the minimal value appears multiple
times in the array

        %Cut nodes
        treeCut(I2);%Tree Cut Node
        idxcuts(I2);%G cut node


        %Edges Removed
        removedTreeEdges{1,I2}(I1(I2),1); %Removed tree edge for
current demand split

        %Nodes on other end
```

```
        otherGnodesearch=EXPotherGnode{I2,I1(I2)};
        otherTreenodesearch=EXPotherTreenode{I2,I1(I2)};

        %Bin or bins for other tree node
        binsearch=[binnodesTree{1,otherTreenodesearch}];

        %What if there is more than one bin? Reduce it to shared bin,
if it is more
        %than one it is likely to be also a cut node
        nbinsearch=numel(binsearch);
        if nbinsearch>1

binsearch=intersect(binsearch,[binnodesTree{1,(treeCut(I2))}]);
        end

        %Get information on possible valve location, define candidate
link and end
        %nodes
        idxsearch=find([binsvalvesreq{I2,:}]==binsearch);
        nvalvessearch=valvesreq{I2,idxsearch};
        % valvesedgereq{I2,idxsearch};
        disp(['Valves required from search: ',num2str(nvalvessearch)])

        if nvalvessearch>1
            matDIFFdemand(I2,I1(I2))=1;
            if  k==numel(splitoptions)
                disp('No alternative location with single valve found,
return to first location')

                %Repeat procedure using original location
                %Edges Removed
                removedTreeEdges{1,ogI2}(ogI1(ogI2),1); %Removed tree
edge for current demand split

                %Nodes on other end
                otherGnodesearch=EXPotherGnode{ogI2,ogI1(ogI2)};
                otherTreenodesearch=EXPotherTreenode{ogI2,ogI1(ogI2)};

                %Bin or bins for other tree node
                binsearch=[binnodesTree{1,otherTreenodesearch}];

                nbinsearch=numel(binsearch);
                if nbinsearch>1

binsearch=intersect(binsearch,[binnodesTree{1,(treeCut(ogI2))}]);
                end

                %Get information on possible valve location, define
candidate link and end
                %nodes
                idxsearch=find([binsvalvesreq{ogI2,:}]==binsearch);
                nvalvessearch=valvesreq{ogI2,idxsearch};
                % valvesedgereq{I2,idxsearch};
                disp(['Valves required from search, using first
location: ',num2str(nvalvessearch)])
                I2=ogI2;
```

```
            end
        else
            k=numel(splitoptions);
            disp('Alternative location with single valve found')
            %Break out of loop
            break
        end



    end

end

for i=1:numel(valvesedgereq{I2,idxsearch})

    %Find the index of the link for the valve and junctions
    [sOut,tOut] =
findedge(GSplit,valvesedgereq{I2,idxsearch}(i));%Retrieves edge index
number of in the GSplit graph
    %Retrieves the EPANET index number using the final split list
    idxsOut=SplitFinal(sOut);
    idxtOut=SplitFinal(tOut);
    %Retrieves the edge index for EPANET using the newly found indices
for each
    %of the nodes
    [findsOut,~]=find(LinkNodeIDX==idxsOut);
    [findtOut,~]=find(LinkNodeIDX==idxtOut);

    linkIDXsearch=intersect(findsOut,findtOut);

    %Search the IDs of the junctions and the edge selected for valve
placement
    EdgeID1{i,1}=LinkName(linkIDXsearch);
    JunctionID1{i,1}=NodeName(idxsOut);
    JunctionID2{i,1}=NodeName(idxtOut);

end

end
```

```
function [newinpname] = ValveSplit2( name, EdgeID,ValveID)
%ValveSplit add a TCV at the middle of the pipe or closer to the
fromNode of the selected link.
%Add pipe segment, TCV,second pipe segment, and delete original pipe.
%Last modified:05/11/2020
%openfile
addpath(genpath(pwd));
inpname=[name,'.inp'];
d=epanet(inpname);

pipeID=EdgeID;

%Define from/to nodes for all links (includes pipes, valves,and pumps)
pipeINDEX=d.getLinkIndex(pipeID);
ConnectedNodesID=d.getNodesConnectingLinksID;
ConnectedNodesIndex=d.getLinkNodesIndex;
```

```
arrayID=d.getLinkNameID;

idx=find(ismember(arrayID,pipeID));
fromto=[ConnectedNodesIndex(idx,:)];

%Get Link Length
LinkLength=d.getLinkLength(pipeINDEX);

%Get node coordinate
coordinates=d.getNodeCoordinates(fromto(1,:));
x1=coordinates(1,1);
y1=coordinates(1,2);
x2=coordinates(2,1);
y2=coordinates(2,2);

pipeRoughness=d.getLinkRoughnessCoeff(idx);
pipeDiameter=d.getLinkDiameter(idx);
elevation=d.getNodeElevations(idx);
newBaseDemand=0;

%Add first link
newNodeID=[ValveID,'_J1'];
newPipeID=[EdgeID,'_U'];
Code='Pipe';

h=sqrt(((x2-x1)^2)+((y2-y1)^2));
offset=0.05*h;
x=(((x2-x1)/h)*offset)+x1;
y=(((y2-y1)/h)*offset)+y1;

newDemandPattern='1';

ToNodeID=ConnectedNodesID{idx,1};
newLength=0.05*LinkLength;
newDiameter=pipeDiameter;
newRoughness=pipeRoughness;

d.addBinJunction(newNodeID,x,y,elevation,newBaseDemand,newDemandPattern
,newPipeID,ToNodeID,newLength,newDiameter,newRoughness,Code);

%Add TCV link
newNodeID=[ValveID,'_J2'];
newPipeID=[ValveID];
Code='TCV';


x3=((((x2-x1)/h)*(0.1))+x;
y3=((((y2-y1)/h)*(0.1))+y;

newDemandPattern='1';

ToNodeID=[ValveID,'_J1'];
newLength=0.1;
newDiameter=****;
newRoughness=pipeRoughness;
```

```
d.addBinJunction(newNodeID,x3,y3,elevation,newBaseDemand,newDemandPatte
rn,newPipeID,ToNodeID,newLength,newDiameter,newRoughness,Code);

%Add second link
newPipeID=[EdgeID,'_D'];

newDemandPattern='1';

ToNodeID=ConnectedNodesID{idx,2};
fromNode=[ValveID,'_J2'];
newLength=0.95*LinkLength;
newDiameter=pipeDiameter;
newRoughness=pipeRoughness;

d.addBinPipe(newPipeID,fromNode,ToNodeID,newLength,newDiameter,newRough
ness);

%Remove link ID
errcode=d.removeBinLinkID(pipeID);

%Save file with new name
ogname='*****’;
newinpname=[ogname,'_',ValveID,'.inp'];
d.saveInputFile(newinpname);

%close all
fclose('all')

end
```

```
function [out,out2,valveList,valveAdjacent,OutList] =
segAssessmentSIMP(inpfn)
%Assessment script structured as a function ONLY FOR TM metric

%Segment based assessment for critical elements. Uses segment and valve
%failure, saves results and can also save workspace variables in *.mat
file
%Function based on previous netAssessment6(inpfn)

% No fire suppression scenario for valves or segments in this script
% Use inpfn to enter the EPANET file name, omit the .INP extension


%If segment files are already loaded comment out sections in
SegmentationValveMOD2
%To graph the network with color-coded segments, uncomment plot
function in
%segmentationValveMOD2

% Function last modified: 06/19/20
%======================================================================
====
%% Function to start segmentation and segment-based analysis (topologic
and supply)
[out,out2,valveList,valveAdjacent]=SegmentationValveMOD4(inpfn);
%% Function to define valve information and effect (length and
topologic)
```

```
%Check paths for secondary isolations considering all segment shutdowns
%Identify segments out of service
INPinfofilename=[inpfn,'INPfileInfo.mat'];
[ BaseDemands,OutList ]=
TestValve(INPinfofilename,valveList,out2,valveAdjacent);
valvemerge_demand=BaseDemands;
% %Save workspace variables
% filename = [inpfn,'_part2.mat'];
% save(filename);
%% Save workspace variables
%Save workspace variables
filename = [inpfn,'.mat'];
save(filename);

disp('End Assessment Function')
end
```

```
function [filename] = NodeInfo_COORD(inpfn)
%NodeInfo_COORD Get INP file information for split/arc node function
%
%% Get node information
%%
%Load Epanet fie
d=epanet([inpfn,'.inp']);

%Get all node coordinates
AllCoordinates=d.getNodeCoordinates;
%Get link names
LinkName=d.getLinkNameID;
%Get node names
NodeName=d.getNodeNameID;
%Retrieves the id of the from/to nodes of all links
NodestoLink=d.getNodesConnectingLinksID;
%Retrieves the index of the from/to nodes of all links
LinkNodeIDX=d.getLinkNodesIndex;
%Retrieve base demands
BaseDemands=d.getNodeBaseDemands;
%Retrieve Node Type Index
NodeType=d.getNodeTypeIndex;
%Build Connectivity Matrix
ConnectivityMatrix_file=d.getConnectivityMatrix;
%Unload Epanet file
d.unload;

%Save variables for later use
filename=[inpfn,'_COORD.mat'];
save(filename,'AllCoordinates','LinkName','NodeName','NodestoLink','Lin
kNodeIDX','BaseDemands','NodeType','ConnectivityMatrix_file');
fclose('all');
end
```

```
function [filename] = CountValveFUN(inpfn,out2)
%CountValveFUN Counts valves by segment
% Count number of valves and differentiate between external and
internal
%valves
%Created:10/11/2019
```

```
%Last Modified:06/19/2020
%%
%Load EPANET file
d=epanet([inpfn,'.inp']);

%Adjecency matrix for nodes
AMatrix=d.getConnectivityMatrix;
LinkNameID=d.getLinkNameID;
%Get number of valves
nvalves=d.getLinkValveCount;
d.unload;

%Load variables from out2 file
boundary = {out2.boundary}.';
ssegments=size(boundary,1);
valveID = {out2.valveID}.';
valveIDX={out2.valveIndex};

%Initialize variables
TotalValveCount=zeros(ssegments,1);
InternalValveCount=zeros(ssegments,1);
UniqueValveCount=zeros(ssegments,1);

%Start valve count
for j=1:ssegments
    valveIDXs=valveIDX{j};
    indUnique=[];
    DuplicateValve_ind=[];
    ExtValveIDX=[];
    TotalValveCount(j)=numel(valveIDXs);
    [~,indUnique]=unique(valveIDXs);
    DuplicateValve_ind=setdiff(1:size(valveIDXs,2),indUnique);
    InternalValveCount(j)=numel(DuplicateValve_ind);
    UniqueValveCount(j)=numel(indUnique);
    ExtValveIDX=setdiff(valveIDXs,valveIDXs(DuplicateValve_ind));
    ExternalValveCount(j)=TotalValveCount(j)-(2*InternalValveCount(j));
    IntValveID(j)={[valveID{j,1}{1,DuplicateValve_ind}]};
    ExtValveID{j}={LinkNameID{1,ExtValveIDX}};
end
filename=[inpfn,'_valveinfo'];
save(filename)
end
```

```
%% Routine for Segments to Split and Candidate Edges for Valve Placement
%Created:06/16/20

% !!! Change name on ValveSplit2 function
% !!! Change inpname variable
getNodeInformationMAT='Coordinates_Names_Info.mat';
networkOutputMAT='*****_v_av_Hyd.mat';
INPfilename='******INPfileInfo.mat';
valveInfoMAT='*****_valveinfo.mat';
namefileMAT='*****_ValveOPT_TM5.mat';

%Change file name on CountValveFUN
%% Set TM tolerance
```

```
TM_limit=0.05;%Maximum allowed value for TM


%% Set list of segments to split
load(networkOutputMAT,'out2','out')

%% Sort topological results
%%
ssegments=size(out2,2);
PrimaryDemandLoss=zeros(ssegments,1);

load(INPfilename,'basedemands_cell')

load(valveInfoMAT,'ExternalValveCount','nvalves')
basedemands=[basedemands_cell{1,1}];

cellDemands=basedemands_cell;
vDemands=[cellDemands{:}];
Nodes = {out2.Nodes}.';

for i=1:ssegments
    PrimaryDemandLoss(i)=sum(vDemands(Nodes{i}));
end

DayDemand=sum(vDemands);

demandLoss = [out.demandLoss].';

%% Topologic (from segAssessment)
% TopologyMetric=[PrimaryDemandLoss, demandLoss-PrimaryDemandLoss,
DayDemand-demandLoss];
pTopologyMetric=[out.PercentageLoss].';
% psortedTopo=pTopologyMetric(idxDemandLoss,:);
ExtValve=ExternalValveCount;


SplitSegList=[5,10,6,125,3];
ResultID=cell(numel(SplitSegList),3);

%% Check TM
% [CritTM,CritID]=max(pTopologyMetric);
TMcheck=0;
i=0;
inpname='******';
IDHydrantMAT='*****_HydInfo.mat';
ogLinksL=[out2.LinksL].';

while TMcheck<1
    [CritTM,CritID]=max(pTopologyMetric);
    if CritTM>TM_limit

        SplitSegList=CritID;
        i=i+1; %Update counter for number of splits

        CritIDsplit(i)=CritID;
        CritTMsplit(i)=CritTM;
```

```
        j=num2str(i);
        Split=CritID;
        disp('Start search for split')
        [EdgeID1,JunctionID1,JunctionID2] =
ArcNodeCoordinatesSPLIT(networkOutputMAT,getNodeInformationMAT,Split);
        ResultID{i,1}=JunctionID1;
        ResultID{i,2}=JunctionID2;
        ResultID{i,3}=EdgeID1;
        disp('Elements for split returned')
        if numel(EdgeID1)>0
            %Split Network
            disp('Start split function')
            ValveID=['V', j];

            [newinpname_valve] = ValveSplit2(inpname,
EdgeID1{:},ValveID);

            %Run new TM assessment
            newfilename=erase(newinpname_valve,'.inp');

            disp('Start assessment')
            [out,out2,valveList,valveAdjacent,OutList] =
segAssessmentSIMP(newfilename);
            pTopologyMetric=[out.PercentageLoss].';

            [filename_COORD] = NodeInfo_COORD(newfilename);
            getNodeInformationMAT=filename_COORD;

            networkOutputMAT=[newfilename,'.mat'];

AddHydrantInfo_seg2(newfilename,networkOutputMAT,IDHydrantMAT)
            INPfilename=[newfilename,'INPfileInfo.mat'];

            %Count valves
            [filenameValveInfo] = CountValveFUN(newfilename,out2);

            %load valve total
            load(filenameValveInfo,'nvalves')
            segmentIDs_Split{i,1}=valveList{1,2};
            segmentIDs_Split{i,2}=valveList{1,4};

            %Get link length
            newLinksL=[out2.LinksL].';
            nsegments=size(out2,2);
            segmentIDs=zeros(nsegments,1);

            %Compare SegmentIDs
            for k=1:numel(newLinksL)
                searchIDs=find(ogLinksL==newLinksL(k));
                if numel(searchIDs)>0
                    segmentIDs(k)=find(ogLinksL==newLinksL(k));
                else
                    segmentIDs(k)=0;
                end
            end

            segmentIDs_Split{i,3}=segmentIDs; %Save IDs
```

```
            ogLinksL=newLinksL;

            inpname = newfilename;
            [CritTM,CritID]=max(pTopologyMetric);

        else
            disp(['ID:',num2str(CritID),' possible bridge']);
            pTopologyMetric(CritID)=0;

            segmentIDs_Split{i,1}=[];
            segmentIDs_Split{i,2}=[];
            segmentIDs_Split{i,3}=[];
        end
    else
        %Condition has been met exit while loop and save results
        disp('User limiting threshold met')
        TMcheck=1;

    end
end

save(namefileMAT);
```

```
function [out,out2,valveList,valveAdjacent,OutList] =
segAssessment(inpfn)
%Assessment script structured as a function

%Segment based assessment for critical elements. Uses segment and valve
%failure, saves results and can also save workspace variables in *.mat
file
% No fire suppression scenario for valves or segments in this script
% Use inpfn to enter the EPANET file name, omit the .INP extension
%If segment files are already loaded comment out sections in
SegmentationValveMOD2
%To graph the network with color-coded segments, uncomment plot
function in
%segmentationValveMOD2

% Function last modified: 05/13/20
%======================================================================
====
%% Overwrite filename
%%%%Name of file used, Remove comment to overwrite FILENAME
% inpfn='FILENAME';
%% Start Assessment
% %Load up path for library
% addpath(genpath(pwd));
%% Function load network file and returns initial results from
hydraulic simulation
[ComputedResults, ComputedPressures] = timeSeriesResults(inpfn);
[ComputedResults_half, ComputedPressures_half] =
timeSeriesResults_half(inpfn);
% NodePressure results are used in Fire Demand Test
NodePressure=ComputedPressures(1,:); %Tanks at initial setting
NodePressure_half=ComputedPressures_half(1,:); %Tanks at half full

nnodes=size(ComputedPressures,2);
%% Function to start segmentation and segment-based analaysis
(topologic and supply)
[out,out2,valveList,valveAdjacent]=SegmentationValveMOD2
(inpfn,nnodes,NodePressure,NodePressure_half);
%Save workspace variables
filename = [inpfn,'_part1.mat'];
save(filename);

%% Function to define valve information and effect (length and
topologic)
%Check paths for secondary isolations considering all segment shutdowns
%Identify segments out of service
INPinfofilename='INPfileInfo.mat';
[ BaseDemands,OutList ]=
TestValve(INPinfofilename,valveList,out2,valveAdjacent);

%Save workspace variables
filename = [inpfn,'_part2.mat'];
save(filename);
%% Save workspace variables
%Save workspace variables
filename = [inpfn,'.mat'];
save(filename);
```

```
disp('End Function')
end
```

```
function [ComputedResults, ComputedPressures] =
timeSeriesResults(inpfn)
%timeSeriesResults Get results from hydraulic and water quality
simulation
%   Get all computed results, pressures are stored as a separate
variable
%Last Modified:06/17/2019
%% Load file and obtain results from initial hydraulic analysis
inpfn=[inpfn,'.inp'];

d=epanet(inpfn);

ComputedResults = d.getComputedTimeSeries;
ComputedPressures=ComputedResults.Pressure;

%Set simulation time
d.setBinTimeSimulationDuration(0*3600);
%Solve all hydraulics and save results
d.solveCompleteHydraulics;
% % hydraulics=d.getComputedHydraulicTimeSeries;
NodeP=d.getBinComputedNodePressure;

d.unload;

fclose all;

end
```

```
function [ComputedResults, ComputedPressures] =
timeSeriesResults_half(inpfn)
%timeSeriesResults Get results from hydraulic and water quality
simulation
%   Get all computed results, pressures are stored as a separate
variable
%Last modified:02/18/20

%% Load file and obtain results from initial hydraulic analysis
inpfn=[inpfn,'.inp'];

d=epanet(inpfn);

nTank=d.getNodeTankCount;

if nTank>0

    TankLevel_Initial=d.getNodeTankInitialLevel;
    TankLevel_Min=d.getNodeTankMinimumWaterLevel;
    TankLevel_Max=d.getNodeTankMaximumWaterLevel;

    TankLevel_Half=TankLevel_Min+((TankLevel_Max-TankLevel_Min)/2);
```

```
else
    disp('No tanks available')
    TankLevel_Half=d.getNodeTankInitialLevel;

end

%Set tanks to half volume
%Set initial tank levels
d.setNodeTankInitialLevel(TankLevel_Half);


ComputedResults = d.getComputedTimeSeries;
ComputedPressures=ComputedResults.Pressure;

%Set simulation time
d.setBinTimeSimulationDuration(0*3600);
%Solve all hydraulics and save results
d.solveCompleteHydraulics;
% % hydraulics=d.getComputedHydraulicTimeSeries;
NodeP=d.getBinComputedNodePressure;

d.unload;

fclose all;

end
```

```
function [out,out2,valveList,valveAdjacent]=SegmentationValveMOD2
(inpfn,nnodes,NodePressure,NodePressure_half)
%Opens the EPANET input file, identifies the segments and creates new
%files. Using original file segments are identified. Routine creates a
copy
%for each segment. Then modifies each of the copies to match the
segment
%analyzed. The performance metrics for Loss of Static demand (*Water
Age
%are estimated, if commented out). This routine executes a pseudo
pressure
%dependent demand simulation for the supply loss metric.

%Open file and identify segments (write original file name in the
routine
%file, it can be overwritten in this routine use FILENAME). File name
%should be entered without .INP extension.

%Output variables: out- summation of demand losses, out2- segment
%information (nodes,links lengths, by ID and by Index), valveList-
includes
%the list of segments that fail linked to the valve failure,
%valveAdjacent-is the segment by segment connectivity matrix.

% When first executed workspace variables are saved throughout
% ('segmentationValveWS.mat','segmentationValveWSmodifiedcopies.mat')
% Comment out section and load these variables if SegmentationValve has
% already been executed and no changes to the segment files are
required
```

```
%Previous update: 02/18/2020
%Last modified:05/13/20
%======================================================================
======
%% Overwrite
%%Overwrite file name
% inpfn='FILENAME.inp';
%% INP file name
name=inpfn;
inpfn=[name,'.inp'];
%% Segment files already created? Use this section
% % %%If sections COMMENTED OUT, UNCOMMENT to LOAD variables
% % load('segmentationValveWS.mat')
% % load('segmentationValveWSmodifiedcopies.mat')
% % %%Define number of segments s
% %s=size(Segment,2);
%% Create segment ID files
%%%%%% Comment out if SegmentID3 files already exist (START)


[filenameMAT] = getINPfileInformation(inpfn); % Function to open EPANET
file and
%obtain basic information. It is done in a external function since
%loadind the file consumes a considerable amount of time

INPinfofilename =filenameMAT;%Load the file obtained from
getINPfileinformation

%Function identifies number of segments
[Segment,valveAdjacent,segment_links]=SegmentID4(INPinfofilename);

%Save variables from segment identification function
filename =[inpfn,'_SegmentID4.mat'];
save(filename,'Segment','valveAdjacent','segment_links');

% load(INPinfofilename) %load EPANET file information
load(INPinfofilename,'valveNameID','LinkNameID','nlinks','LinkNameID');
%load EPANET file information

%Make copies
[ output,s ]=segmentCopy( name,Segment );
disp(output);

%List of node index types
load(filenameMAT, 'NodeIndexType','nSource')
% [NodeIndexType,nSource] = ListNodeIndex(inpfn); %Initial function to
% obtain characteristics. Replaced by getINPfileInformation

%Output file and message
disp('Copies completed')

oldinpname=[name,'.inp'];
out2=Segment;

%Saves worspace variables up to this point
save('segmentationValveWS.mat')
```

```
% Set number of workers M, there might issues with stability if too
high in
% some machines
%
load(INPinfofilename,'valveNameID','LinkNameID','nlinks','LinkNameID');
%load EPANET file information
load(INPinfofilename,'nlinks');
load(INPinfofilename,'LinkNameID');
load(INPinfofilename,'valveNameID');

M=2;
s=size(Segment,2);
segSecond=cell(1,s);
nsecondIsolation=zeros(1,s);

in_allvalves=valveNameID;
copy_LinkNameID=LinkNameID;
copy_nlinks=nlinks;

% temp=cell(1,s);
% tempPIPE=cell(1,s);

for i=1:1:s
    %Identify secondary isolation

[nisolated,segmentlist,remove,removePipe,allvalves]=secondIsolation3(Se
gment,i,in_allvalves,segment_links,copy_nlinks,copy_LinkNameID,valveAdj
acent);

    segSecond{1,i}={segmentlist};
    nsecondIsolation(1,i)=nisolated;

    %     temp{1,i}=remove;
    %     tempPIPE(1,i)=removePipe;
    Segment(i).removed=remove;
    Segment(i).removedPIPE=removePipe;
    Segment(i).removedVALVES=allvalves;
end

parfor (i=1:1:s,M)
    %Modify copies based on secondary isolations
    j=num2str(i);
    inpname=[name,'_',j,'C.inp'];
    remove=Segment(i).removed;
    removePipe=Segment(i).removedPIPE;
    allvalves=Segment(i).removedVALVES;
    [~, ~,~] = modifyCopy6(inpname,remove,removePipe,allvalves); %Use
this modify with secocondisolation3
    disp(['i:',num2str(i)])
end

out2=Segment;
%Output file and message
disp('Completed copy modifications')

%Saves workspace variables
```

```
save('segmentationValveWSmodifiedcopies.mat')
%%%%%% Comment out if files already exist (END)

%% Quantify topologic and pseudo-pressure dependent metrics
% Check segments to skip (those without any sources available)

% load(INPinfofilename,'basedemands_cell','nodeNameID')%Load variables
needed for the loop
load(INPinfofilename,'basedemands_cell');
load(INPinfofilename,'nodeNameID');

load(INPinfofilename,'nodeIndexTypeList');

run_s=zeros(s,1);
%Try with parfor on next run
for i=1:1:s
    %% Check topologic based demand loss
    removed=out2(i).removed;
    % [removedIndex]=IDtoIndex(inpfn,removed);
    removedIndex=[];
    for k=1:numel(removed)
    rem_index=find(strcmp(nodeNameID, removed{k}));
    [removedIndex]=[removedIndex,rem_index];
    end
    [ demandLoss ] =
StaticDemand6(name,removed,INPinfofilename,basedemands_cell,nodeNameID
);

    %filename for epanet modified copy
    j=num2str(i);
    inpname=[name,'_',j,'C'];
    %% Check if sources are available
    %Check if there are sources available after shutdown (even when
elements
    %are not deleted)| 1, means run|2, means skip.
    IndexSourceremoved=nodeIndexTypeList(removedIndex);

nSourceremoved=numel(find(IndexSourceremoved==1))+numel(find(IndexSourc
eremoved==2));
    if nSource-nSourceremoved>0
        run_s(i)=1;
    else
        run_s(i)=2;
    end
    %% Store topologic
    static(i).demandLoss=demandLoss;
end

for i=1:size(static,2)
static(i).run=run_s(i);
end

out=static;

for i=1:1:s
    %% Start pseudo-pressure dependent loss of supply estimate
    %filename for epanet modified copy
```

```
    j=num2str(i);
    inpname=[name,'_',j,'C'];
    if static(i).run==1
        %% Tank water elevation at initial

%%%%==================================================================
==
        %%Uncomment function for staticSupply to use setting with tanks
to
        %%initial setting for volume. This function executes a
hydraulic
        %%simulation.
        %
[topologySupply,listSupply]=staticSupply(inpname,NodePressure);

%%%%==================================================================
==
        %% Tank water elevation at half volume

%%%%==================================================================
==
        %%%Set tanks to half volume and run pressure simulation
        %%%Verify that the node pressure variable used matches the
intended
        %%%supply function. This function executes a hydraulic
simulation.

[topologySupply,listSupply]=staticSupply_half(inpname,NodePressure_half
);

%%%%==================================================================
==

    else
        topologySupply=0;
        listSupply=zeros(1,nnodes);
    end
    %% Store supply shortage results
    static(i).Supply=topologySupply;
    static(i).listSupply=listSupply;
end
out=static;
%% Base Demand Total
% %Get base demand total
% [ TotalDemand ] = getSumBaseDemand( oldinpname );%Using INP file
basedemands=basedemands_cell{1,1};
[TotalDemand]=sum(basedemands,2);

disp('check 1: Estimate base demand total for original system.
Topologic and pseudo-PPD completed.')

%%%==================================================================
====
%% Variables for Figures and Graphs
%%Define variables for figures and graphs

numSegments=numel(static);
```

```
Loss=zeros(1,numSegments);
LossSupply=zeros(1,numSegments);

parfor p=1:numSegments
    Loss(1,p)=static(p).demandLoss;
    LossSupply(1,p)=TotalDemand-static(p).Supply;
end

LossP=Loss;

%Loss as a percentage
LossP=LossP./TotalDemand;
perLossS=LossSupply./TotalDemand;

%M specifies maximum number of workers when parfor is used
M=2;
parfor (i=1:1:s,M)
    %     static(i).age=Age(i);
    %     static(i).MaxAge=MaxAge(i);
    %     static(i).NodeIndex=NodeIndex(i);

    % %     diffAgeC(i)={diffAge};
    %     static(i).diffIdx=diffIdx(i);
    %     static(i).maxDiff=maxDiff(i);
    %     static(i).diffAgeC=diffAgeC{i};
    %
    %     static(i).WQe=WQeffect(i);

    static(i).PercentageLoss=LossP(i);
    static(i).PercentageSupplyLoss=perLossS(i);
    static(i).LossSupply=LossSupply(1,i)

end

out=static;

%% Plot of the network with color-coded segments
%=======================================================================
=======
% %Add Plot of Network, segments will be color coded
%
% numSegments=numel(out2);
%
% for p=1:numSegments
%     %Addedd {1,1} element by element call
%     numID=numel(out2(p).LinksID);
%
%
%     pipeID{1,p}=out2(p).LinksID;
%
% end

% % pipeID.
% %Plot of network is added. Comment out if not required
%
% PlotColor2(oldinpname, pipeID);
%
```

```
% %End of plot command
%==========================================================================
=======

%% Identify segments adjacent to each valve
%Identify segments associated with a valve
load(INPinfofilename,'allValvesIndex');
valveIndex = {out2.valveIndex}.';
allValves=allValvesIndex;

nvalves=numel(allValves);%number of valves
nSegments=numel(valveIndex);%number of segments

for j=1:nvalves

    segCount=[];
    valve=allValves(j);
    valveList{j,1}=valve;
    Lenght2=0;
    IDvalve=LinkNameID(valve);

    for i=1:nSegments
        test=find(valveIndex{i,:}==valve);
        if numel(test)>0
            segCount=[segCount,i];
            Lenght2=Lenght2+out2(i).LinksL;
        end
    end

    valveList{j,2}=segCount;
    valveList{j,3}=Lenght2;
    valveList{j,4}=IDvalve;

end
disp ('Check 5: Initial valve information compiled')

%% Save files
variablenames=[{'out'},{'out2'},{'valveList'},{'valveAdjacent'}];
filename = [inpfn,'_OutputSegmentation.mat'];
save(filename,'out','out2','valveList','valveAdjacent');

end
```

```
function [filenameMAT] = getINPfileInformation(inpfn)
%getINPfileInformation Launches the EPANET file and obtains element
%information
%   EPANET file is loaded and several functions to identify the
elements
%   and the characteristics are used. The results are saved to later be
%   used by other functions without requiring the reload of the network
%   file since repeated loading can be time consuming.

%%
%start epanet
d=epanet(inpfn);

%Get all connecting nodes by link
```

```
[fromto]=d.getLinkNodesIndex;
from=fromto(:,1);
to=fromto(:,2);

%Set the toal number of links
nlinks=d.getLinkCount;

%Set the total number of nodes
nnodes=d.getNodeCount;

%Set a link type index list
LinkIndexTypeList=d.getLinkTypeIndex;

%Set a node type index list
nodeIndexTypeList = d.getNodeTypeIndex;
% Get all link types
typeIndex=d.getLinkTypeIndex;

%Set a valve index list
allValvesIndex=d.getLinkValveIndex;

%Set a link index list
allLinksIndex=d.getLinkIndex;

%Set up the list of names for the nodes and links
nodeNameID=d.getNodeNameID;
LinkNameID=d.getLinkNameID;
valveNameID=d.getLinkValveNameID;

%All link lengths
LinkLengths=d.getLinkLength;


%Get base demands (as cell)
basedemands_cell=d.getNodeBaseDemands;

%Entries from ListNodeIndex function needed for the
SegmentationValveMOD2
NodeIndexType=nodeIndexTypeList;
nSource=numel(find(NodeIndexType==1))+numel(find(NodeIndexType==2));

%Get source count
nsource=d.getNodeTankReservoirCount;
%Get tank and reservoir count(different name for fire flow function)

 %% Save variables and unload file
%
variablenames=[{'inpfn'},{'fromto'},{'from'},{'to'},{'nlinks'},{'nnodes
'},{'LinkIndexTypeList'},{'nodeIndexTypeList'},{'nodeNameID'},{'LinkNam
eID'},{'valveNameID'},{'LinkLengths'},{'typeIndex'},{'NodeIndexType'},{
'nSource'},{'basedemands_cell'},{'allValvesIndex'},{'nsource'}];

filename ='INPfileInfo.mat';
save(filename,'inpfn','fromto','from','to','nlinks','nnodes','LinkIndex
TypeList','nodeIndexTypeList','nodeNameID','LinkNameID','valveNameID','
LinkLengths','typeIndex','NodeIndexType','nSource','basedemands_cell','
allValvesIndex','allLinksIndex','nsource')
```

```
filenameMAT=filename;

d.unload;
fclose all;
end
```

```
function
[Segment,valveAdjacent,segment_links]=SegmentID4(INPfileInfomat)
%SegmentID4 This function identifies the segments in a network given
the file
%information
%   Run the getINPfile information function first to load the INP file
and
%   obtain the basic information of the system. This function only
%   identifies the segments, its components and boundaries. In order to
%   identify secondary isolations run the secondIsolation or similar
%   function on file
% Original function:05/12/20
% Last modified:06/08/20 %Added PRV to function as isolation valve
%% Load variables from INP file
load(INPfileInfomat,
'nnodes','typeIndex','nlinks','to','from','LinkLengths','nodeIndexTypeL
ist','nodeNameID','LinkNameID');
 %% Build system matrix
%Build matrix representation of system, index numbers are used for
nodes
%and pipes. The columns of the matrix are the links while the rows of
the
%system are the nodes

for i=1:nnodes
    Nodes(i).boundary=0;
end

%% Classify link types
pumpIndex=find(typeIndex==2);
valveIndex=find(typeIndex==7); %Index for TCV valves, add any other
types if necessary.
valveIndexPRV=find(typeIndex==3); %Index for PRV valves
if numel(valveIndexPRV)>0
valveIndex=[valveIndex,valveIndexPRV];
end
%% Define connectivity matrix and characteristics for links/nodes
A=zeros(nnodes,nlinks);
for l=1:1:nlinks
    ni=from(l);
    nf=to(l);
    A(ni,l)=1;
    A(nf,l)=1;
    % %     Get legth and assign values to the link structure
    Links(l).Length=LinkLengths(l);
    Links(l).node1=ni;
    Links(l).node2=nf;
    length= Links(l).Length;
```

```
    if ismember(l,valveIndex)>0
        %Check if the element is a valve, check the list of index types
        %considered isolation valves
        %Element is not a pump, it is a defined valve
        Nodes(ni).boundary=1;
        Nodes(nf).boundary=1;
        Nodes(ni).valve=l;
        Nodes(nf).valve=l;
        Links(l).valve=1;
    else
        %Link element is not a valve
        Links(l).valve=0;
    end
end

%% Build a list of connected pipes for each node (listed by index)

nsource=0;

for k=1:1:nnodes
    pipelist=[];
    for l=1:1:nlinks
        if A(k,l)==1
            pipelist=[pipelist,l];
        end
    end
    Nodes(k).pipes=pipelist;
    check(k)=0;

    if nodeIndexTypeList(k)==0
        %Junctions are type index 0
        Nodes(k).source=0;
    else
        %Tanks or reservoir (Type index 2 and 1)
        Nodes(k).source=1;
        nsource=nsource+1;
    end
end
 %%
%%%Check how nodes are stored in the structure. Use for verification
when
%%%necessary
% T = struct2table(Nodes)

%% Identify the segments
s=0;
%Check node type for start node (nnode)
ctype=nodeIndexTypeList(nnodes);
disp('Start node type: ');
disp(ctype);

for c=nnodes:-1:1

    if check(c)==1
    else
        s=s+1;
```

```
        [SegmentNodes,Segmentboundary,SegmentEnd,SegmentLinks,
check]=checknode( c, Links, Nodes,check,[],[],[],[]);
        Segment(s).Nodes=SegmentNodes;
        Segment(s).boundary=Segmentboundary;
        Segment(s).End=SegmentEnd;
        Segment(s).Links=unique(SegmentLinks);

        segnodes=size(SegmentNodes,2);
        Segment(s).source=0;

        for m=1:1:segnodes
            if Nodes(SegmentNodes(m)).source==1
                Segment(s).source=1;
            end
        end

    end

end

% Write checked list to nodes structure.Use for verification when
necessary
for i=1:nnodes
    Nodes(i).check=check(1,i);
end

%% Retrieve the name IDs for nodes and links (by index)
for i=1:s
    nodesID=[];
    LinksID=[];
    boundaryID=[];
    tnodes=size(Segment(i).Nodes,2);
    LinksLength=[];

    nodesID=[nodeNameID(Segment(i).Nodes)];
    Segment(i).NodesID=nodesID;

    LinksID=[LinkNameID(Segment(i).Links)];
    Length=[LinkLengths(Segment(i).Links)];
    LinksLength=sum(Length);

    Segment(i).LinksID=LinksID;
    Segment(i).LinksL=LinksLength;
    tboundary=size(Segment(i).boundary,2);

    boundaryID=[nodeNameID(Segment(i).boundary)];
    Segment(i).boundaryID=boundaryID;
end

%%
%%Saves workspace variables. Use this to check/verify function
% filename = 'PARTsegmentationTestFile.mat';
% save(filename);

%% Retrieve valve IDs
for k=1:s
    valveID=[];
```

```
    nvalves=size(Segment(k).boundary,2);
    for j=1:nvalves
        nodeIndex=Segment(k).boundary(j);
        Segment(k).valveIndex(j)=Nodes(nodeIndex).valve;
    end

    valveID = [LinkNameID(Segment(k).valveIndex)];
    Segment(k).valveID=valveID;
end

%% Define incident segments
segment_links=zeros(s,nlinks);
sz=[s,nlinks];

for k=1:s
    col=Segment(k).valveIndex;
    row=k.*ones(1,numel(col));
    ind=sub2ind(sz,row,col);
    segment_links(ind)=1;
end

for k=1:s
    sharedvalves=[];
    incidentsegments=[];
    segment_1=ones(s,1);
    matrix_s=segment_links(k,:).*segment_1;
    matrix_inc=matrix_s.*segment_links;
    matrix_inc(k,:)=zeros(1,nlinks);
    [row, col]=find(matrix_inc==1);
    incidentsegments=setdiff(unique(row),k);
    sharedvalvesIDX=unique(col);
    Segment(k).Incident=incidentsegments;
end

%Valves that only list one incident segment are internal valves

%% Build segment adjacency matrix
valveAdjacent=zeros(s);
for i=1:s
valveAdjacent(i,[Segment(i).Incident])=1;
end

end
```

```
function [nodes,boundary,endn,spipes,check] = checknode( c, Links,
Nodes,check,nodes, boundary, endn,spipes)
%Recursive function to identify segments given a start node
%  Uses structures as inputs and outputs
%         T = struct2table(Links)
%         T = struct2table(Nodes)

if check(c)==0
    if Nodes(c).boundary==1
        boundary=[boundary,c];
    else
        if size(Nodes(c).pipes,2)==1
```

```
            endn=[endn,c];
        end
    end

    check(c)=1;
    numpipes=size(Nodes(c).pipes,2);
    nodes=[nodes,c];

    for m=1:numpipes
        pipeindex=Nodes(c).pipes(m);
        if Links(pipeindex).valve==0;
            spipes=[spipes,pipeindex];
            %define end node

            if Links(pipeindex).node1==c
                endnode=Links(pipeindex).node2;

            else
                endnode=Links(pipeindex).node1;
            end

            if check(endnode)==1
                %Already visited
            else
                if Nodes(endnode).boundary==1

                    boundary=[boundary,endnode];
                    nodes=[nodes,endnode];
                    check(endnode)=1;

                else
                    if size(Nodes(endnode).pipes,2)==1
                        nodes=[nodes,endnode];
                        endn=[endn,endnode];
                        check(endnode)=1;

                    else
                        [nodes,boundary,endn,spipes,check]
=checknode(endnode,Links, Nodes,check,nodes, boundary, endn,spipes);

                    end
                end
            end

            %added end
        end
    end



end
end
```

```
function [ output,i ] = segmentCopy( name,structure )
%Creates a file copy for each segment identified
%   The function creates a copy for each segment identified, the new
```

```
%   filename includes: the original file name, the segment number and
%   C as a suffix.
%% Create file copies
n=size(structure,2);

for i=1:1:n
    SaveInpCopy(name,i);
end

n=num2str(n);
output=['New files created: ',n];

fclose all;
end
```

```
function [nisolated,segmentlist,remove,removePipe,allvalves] =
secondIsolation3(Segment,i,in_allvalves,segment_links,nlinks,LinkNameID
,valveAdjacent)
% Identifies secondary isolations for failure of segment i and "Removes
links" Based on list of segment elements
% The "removed" elements are modified. The base demands are set to zero
and
% links are closed. Original version physically deleted pipes (see
older
% versions of the function to view these commands)
% Function last modified/reviewed: 05/12/2020
%Initiate variables
remove=[];
allvalves=[];
removePipe=[];

%Identify the total number of segments for the file analyzed
s=size(Segment,2);

CopySegment=Segment;
Source=[];

% Create a copy of the segment structure where previous results are
saved
for k=1:1:s
    CopySegment(k).Incident=setdiff(Segment(k).Incident,i);
    CopySegment(k).check=0;
end

%Find the number of segments with sources in the network
Source=find([CopySegment.source]==1);
Source=setdiff(Source,i); %Dont't include the segment failed in the
sources

% Define the number of sources available in the network
nsource=size(Source,2);
check=[];

% Check elements that are considered sources
TankNodeCount=sum([Segment.source]);

% Check if the number of sources is inconsistent
```

```
if(nsource+CopySegment(i).source<TankNodeCount)
    disp('Check number of sources -is there a segment with multiple
sources? (tanks,reservoirs)')
    disp('Review segment')
    disp(i);
    nisolated=0;
    segmentlist=[];
end

%% Define paths from the source segments
if nsource>0 % Sources are available. At least one source is present in
the network
    %%% Define the paths available from the source to the segments
(which
    %%% segments can still be reached if the current segment is taken
out)

    valveAdjacent2=valveAdjacent;%Copy of segment adjacency matrix
    valveAdjacent2(i,:)=zeros(1,s); %Failed segment is disconnected,
make row zero
    valveAdjacent2(:,i)=zeros(s,1); %Failed segment is disconnected,
make column zero

    reached=[];

    for k=1:nsource
        segID=Source(k); % Use the list or sources to define the
segment ID
        % Define a graph structure using the segment adjacency matrix
        G=graph(valveAdjacent2~=0);
        check=bfsearch(G,segID);%Use breadth first search departing
from a
        %defined source segment
        check=unique(check)';
        path(k).segments=check; %Store reachable path for the given
source

        reached=[reached,check];

        %          %Uncomment to check paths for each segment
        %          disp('path followed')
        %          disp(check)

    end

    reached=unique(reached);

    % %Uncomment to checked reached segments listed
    %     disp('path followed')
    %     disp(reached)

    %% List of unintended segments that have been isolated
    segmentlist=1:1:s; %List of all segments
    segmentlist=setdiff(segmentlist,i); %Remove currently failed
segment
```

```
    segmentlist=setdiff(segmentlist,reached);%From segment list removed
all
    % segments that can be reached from one of the remaining sources

    nisolated=size(segmentlist,2);

    % disp(nisolated)

    % Find all shared valves between principal segment and neighboring
    % segments
    sharedvalves=[];

    segment_1=ones(s,1);
    matrix_s=segment_links(i,:).*segment_1;
    matrix_inc=matrix_s.*segment_links;
    matrix_inc(i,:)=zeros(1,numel(nlinks));
    [~, col]=find(matrix_inc==1);
    sharedvalvesIDX=unique(col);
    sharedvalves=LinkNameID(sharedvalvesIDX);
    nsharedvalves=size(sharedvalves,2);

    % Update list of all valve IDs including the secondary isolations
    %Find all valves
    %Pull a submatrix using the segment analyzed and secondary
isolations

    [~,allvalvesIDX_s]=find(segment_links([i,segmentlist],:)==1);
    allvalvesIDX_s=unique(allvalvesIDX_s);
    allvalvesID=[LinkNameID(allvalvesIDX_s)];


    disp(['segment:',num2str(i)])

    % List of the nodes and pipes to eliminate
    remove=[];
    remove=[Segment(i).NodesID];% Add node ID list from original
segment failed
    removePipe=[];
    removePipe=[Segment(i).LinksID];% Add ID list from original
shutdown (if no unintended isolations occur)

    allvalves=allvalvesID;

    for j=1:nisolated
        m=segmentlist(j);
        % List pipes from initial shutdown and unintended isolations
        removePipe=[removePipe,Segment(m).LinksID];
        remove=[remove,Segment(m).NodesID];% List pipes from initial
shutdown and unintended isolations
    end

else
    % No sources remain available
    disp('Only source was eliminated')
    nisolated=s-1;
    segmentlist=1:1:s;
    segmentlist=setdiff(segmentlist,i);
```

```
    for m=1:s
        remove=[remove,Segment(m).NodesID]; % Compiling all Node IDs
    end


    allvalvesID=in_allvalves;
    removePipe=LinkNameID;
    removePipe=setdiff(LinkNameID,allvalvesID); %Remove the valve IDs
from
    % the links that need to be removed

end
%% Review that there are no duplicates
remove=unique(remove);
removePipe=unique(removePipe);
allvalves=unique(allvalvesID);

Segment(i).removed=remove;
Segment(i).removedPIPE=removePipe;
end
```

```
function [remove, removePipe,allvalves] = modifyCopy6(
inpname,remove,removePipe,allvalves)
% "Removes links" Based on list of segment elements
% The base demands are set to zero and links are closed. Original
version
% physically deleted pipes, these commands are commented out.
%Function previously modified/reviewed:05/13/2020
%Function last modified/reviewed: 05/19/20 %Check for CV and valve
%modifications
%% Load file to be modified
d=epanet(inpname);

%% Load results from second isolation function

remove=unique(remove);
nremove=size(remove,2);

removenodeINDEX=d.getNodeIndex(remove);

% disp(allvalves)
removevalveINDEX=d.getLinkIndex(allvalves);
% disp(valveINDEX)
% disp(removePipe)
removepipeINDEX=d.getLinkIndex(removePipe);

LinkTypeINDEX=d.getLinkTypeIndex(removepipeINDEX);
CVPipe=removepipeINDEX(LinkTypeINDEX==0);%Check if there are any
control valves

%% Modify existing file
%Zero demands
X=zeros(1,nremove);

% Set zero demands at nodes
d.setNodeBaseDemands(removenodeINDEX,X);
```

```
% Close all pipes
%Verify that no check valves are being modified (will trigger an
error);
if numel(CVPipe>0)
    removepipeINDEX_CV=setdiff(removepipeINDEX,CVPipe);
else
    removepipeINDEX_CV=removepipeINDEX;
end

X=zeros(1,numel(removepipeINDEX_CV));
d.setLinkInitialStatus(removepipeINDEX_CV,X);
X=zeros(1,numel(removevalveINDEX));
d.setLinkInitialStatus(removevalveINDEX,X);

% Verify that changes have been made
LinkStatusCheck_V=d.getLinkInitialStatus(removevalveINDEX);
if sum(LinkStatusCheck_V)>1
    disp(['Verify file for segment:',inpname])
end

% d.getLinkStatus

%% Save Changes
%d.saveInputFile(inpname,d.BinTempfile);
d.saveInputFile(inpname);

% % Test saved network
% %Plot saved network
% d.Binplot;

d.unload;

fclose all;

end
```

```
function [ demandLoss ] = StaticDemand6(
name,removed,INPinfofilename,basedemands_cell,nodeNameID )
%Calculate estatic demand loss as a consequence of segment failure
%   Input uses the name of the input file and the elements that need to
be
%   removed

inpname=[name,'.inp'];
Loss=0;
nnodes=size(removed,2);
allnodeIndex=zeros(1,nnodes);
nodeIndex=0;
value=0;
basedemands=basedemands_cell{1,1};
% disp(basedemands)

for i=1:nnodes
    Nodeid=removed{i};
```

```
    %     disp('Nodeid')
    %     disp(Nodeid)
%     nodeIndex=d.getBinNodeIndex(Nodeid);%Use when epanet file is
loaded

nodeIndex = find(strcmp(nodeNameID,Nodeid));
    %     disp(nodeIndex)
    %Code 9 : actual demand, Code 1: base demand
    %     disp(basedemands)
    %     disp(nodeIndex)
    value=basedemands(1,nodeIndex);
    Loss=Loss+value;
    allnodeIndex(i)=nodeIndex;

end

demandLoss=Loss;

end
```

```
function [sumS,S] = staticSupply_half(name,NodePressure)
inpname=[name,'.inp'];
d=epanet(inpname);

basedemands=d.getNodeBaseDemands;
basedemands=basedemands{1,1};


nTank=d.getNodeTankCount;
idxTank2=d.getNodeTankIndex;

%Define tank half volume
%Volume.Tank volume is given in cubic feet or cubic meter.
%Do not use getNodeTankVolume function

if nTank>0

%     TankVolume2=d.getNodeTankMaximumWaterVolume(idxTank2);
%     Tank2=[idxTank2' TankVolume2'];
%     TankDiameter2=d.getNodeTankDiameter(idxTank2);

    TankLevel_Initial=d.getNodeTankInitialLevel;
    TankLevel_Min=d.getNodeTankMinimumWaterLevel;
    TankLevel_Max=d.getNodeTankMaximumWaterLevel;

    TankLevel_Half=TankLevel_Min+((TankLevel_Max-TankLevel_Min)/2);


else
    disp('No tanks available')
    TankLevel_Half=d.getNodeTankInitialLevel;

end

%Set tanks to half volume
%Set initial tank levels
d.setNodeTankInitialLevel(TankLevel_Half);
```

```
%Recall time series data
d.setTimeSimulationDuration(0*3600);
timeseriesResults=d.getComputedTimeSeries;

Pressure=timeseriesResults.Pressure;
Pressure=Pressure(1,:);

%Get units of network model
units=d.getBinUnits;

%Pressure reference
refunitsP={'psi','meters'};
refPmin=[35, 24.61];
%refPmin=[20, 14.06];
%refPmin=[40, 28.12];
pressure=units.BinNodePressureUnits;
idxP=find(ismember(refunitsP,pressure));
% Pmin=refPmin(idxP);
Pmin=refPmin(idxP);
Pmin2=refPmin(idxP)*ones(1,size(Pressure,2));
S=zeros(1,size(Pressure,2));

Pref=NodePressure;

% Pdes=NodePressure;
% Pdes(Pdes<Plim)=Plim;

D=basedemands;
P=Pressure;

S(P<Pmin)=0;

P(P>Pref)=Pref(P>Pref);
P(P<Pmin)=Pmin;

nodes_above=find(Pref>Pmin);

S(nodes_above)=D(nodes_above).*sqrt((P(nodes_above)-
Pmin2(nodes_above))./(Pref(nodes_above)-Pmin2(nodes_above)));
S(Pref<Pmin)=0;
S(P>Pref)=D(P>Pref);


sumS=sum(S);

end
```

```
function [ BaseDemands,OutList ] = TestValve(
INPinfofilename,valveList,out2,valveAdjacent)
%Calculates static demand linked to valve failure and list of shutdown
nodes
% The function considers ALL valves even those that have not been
% considered for segmentation(i.e., anything else than a TCV unless
changed
% in segmentID script
%Previously updated/reviewed: 05/13/2020
```

```
%Last updated/reviewed: 05/20/2020 %changed indexing for some for
loops, i
%counter was being overwritten.

%% Load INP file information
load(INPinfofilename);
%% Define demand loss and length afected by valve
numValve=size(valveList,1);
BaseDemands=zeros(numValve,1);
for i=1:numValve
    %Define segment shutdown for valve
    segList=valveList{i,2};
    m=numel(segList);
    IDlist=[];
    IDlistPIPE=[];

    %List IDs for nodes that should be erased
    for j=1:m
        k=segList(j);
        IDlist=[IDlist, out2(k).removed];
        IDlistPIPE=[IDlistPIPE, out2(k).removedPIPE];
    end

    %Check paths for secondary isolations considering all segment
shutdown
    %Identify segments out of service
    connectivityMatrix=valveAdjacent;
    nsegment=size(out2,2);
%     ind1=sub2ind(size(connectivityMatrix),seglist,1:1:nsegment);
%     ind2=sub2ind(size(connectivityMatrix),1:1:nsegment,seglist);

    connectivityMatrix(segList,1:1:nsegment)=0;
    connectivityMatrix(1:1:nsegment,segList)=0';

    for j=1:nsegment
        SegmentStructure(j).ID=j;
        SegmentStructure(j).source=out2(j).source;
        SegmentStructure(j).check=0;
        if any(segList==j)
            SegmentStructure(j).source=0;
            SegmentStructure(j).check=1;
        end
    end

    sourcelist=[SegmentStructure.source];
    sourcelist=find(sourcelist==1);
    storepath=[];

    for j=1:numel(sourcelist)
        pathlist=[];
        [pathlist, storepath,SegmentStructure] =
checksegment(sourcelist(j),connectivityMatrix,pathlist,storepath,Segmen
tStructure);
    end

    npathways=size(storepath,2);
    secList=[1:1:nsegment];
```

```
    if npathways>0
        sequence2 = {storepath.sequence}.';
    else
        sequence2=[];
    end

    secIDlist=[];
    secIDlistPIPE=[];

    for j=1:npathways
        secList=setdiff(secList,sequence2{j,1});
    end

    %     secList=[secList,segList];
    %     secList=unique(secList);

    for j=1:numel(secList)
        k=secList(j);
        secIDlist=[secIDlist, out2(k).removed];
        secIDlistPIPE=[secIDlistPIPE, out2(k).removedPIPE];
    end

    %Erase duplicate IDs
    IDlist=unique(IDlist);
    IDlistPIPE=unique(IDlistPIPE);
    %Save list of nodes for each valve
    OutList(i).NodeList=IDlist;
    OutList(i).PipeList=IDlistPIPE;


    %Erase duplicate IDs from secondary list
    secIDlist=unique(secIDlist);
    secIDlistPIPE=unique(secIDlistPIPE);
    %Save list of nodes for each valve
    OutList(i).secNodeList=secIDlist;
    OutList(i).secPipeList=secIDlistPIPE;

    for j=1:numel(secIDlist)
        secIDXlist(j,1)=find(strcmp(nodeNameID,secIDlist(j)));
    end

    for j=1:numel(secIDlistPIPE)
        secIDXlistPIPE(j,1)=find(strcmp(LinkNameID,secIDlistPIPE(j)));
    end

    %Check base demand using secondary isolation list (loss of demand
from
    %isolations)
    NodeList=secIDXlist;
    B=basedemands_cell;
    B=cell2mat(B);
    C=sort(NodeList);
    B1=B(C);
    B=sum(B1);
    BaseDemands(i)=B;
```

```
    %nsource from INPinfofilename

nsource=numel(find(nodeIndexTypeList==1))+numel(find(nodeIndexTypeList=
=2));
    NodeIndex=nodeIndexTypeList(C);
    nsource2=numel(find(NodeIndex==1))+numel(find(NodeIndex==2));
    diff=nsource-nsource2;
    OutList(i).Diff=diff;

    LinkList=secIDXlistPIPE;
    Lengths=LinkLengths;
    Lengths2=Lengths(LinkList);
    OutList(i).secLength=sum(Lengths2);

end
end
```

```
function [] =FireDemandTest5(inpname_in)
% %Run fire demand metric/test
%  Last updated:10/02/2019
% Last modified:05/25/20
% %Load results from segmentation and initial analysis
% % filename=[inpname,'.mat'];%%Name of the file, overwritten for test
% % load (filename); %%Temporarily commented out for test, and
overwitten on next line
load('******.mat','out','out2','NodePressure')
nsegments=size(out,2);

AllHydSupply=cell(nsegments,1);
FFHydrant=cell(nsegments,1);

D_ffd=zeros(1,nsegments);
FF_ffd=zeros(1,nsegments);
removed = {out2.removed}.';
removedPIPE = {out2.removedPIPE}.';
inpfn=[inpname_in,'.inp'];
d=epanet(inpfn);
TankResCount=d.getNodeReservoirCount+d.getNodeTankCount;
notskip=zeros(nsegments,1);

notskip=[];
M=2;

TESTNodesHyd2={out2.TESTNodesHyd}';

parfor (s=1:nsegments,M)
    a=s;
    %    %Check which segment is running
    %    disp(a)
    v=0;
    %IndexList=d.getNodeIndex(removed{s,1});
    removedlist=removed{a,1};
    j=num2str(a);
    inpname2=[inpname_in,'_',j,'C.inp'];
    [IndexList,TypeIndex] =
AUXgetNodeIndexandType(inpname2,removedlist);
    IndexCount=numel(TypeIndex(TypeIndex>0));
```

```
    nHydrants= size(TESTNodesHyd2{s,1},2); %Cell size of cell 1 by
nHydrants

    if TankResCount>IndexCount
        %Check if hydrants are available
        if nHydrants>0
            v=1;
        end
    end
    exitvariable(s)=v;
end
notskip=find(exitvariable==1);


%Create empty arrays for variables
meanSupply=zeros(1,nsegments);
maxSupply=zeros(1,nsegments);
minSupply=zeros(1,nsegments);

idxMax=zeros(1,nsegments);
idxMin=zeros(1,nsegments);

normFF=zeros(1,nsegments);

D_ffd=zeros(1,nsegments);

FF_ffd=zeros(1,nsegments);

%Start variables
AllHydSupply=cell(1,nsegments);
FFHydrant=cell(1,nsegments);

idNodes={out2.removed}';
idxFireHydrants={out2.TESTNodesHyd}';
NodePressure2=NodePressure;

parfor (s=1:nsegments,2)

    if ismember(s,notskip)
        i=s;

        s_name=[inpname_in,'_', num2str(i),'C'];
        [ffdHyd,ff,nHydrants,SumMaxDayDemand,outSupply]  =
FireDemand5(s_name,i,idNodes{s,1},idxFireHydrants{s,1},NodePressure2);

        meanSupply(s)=outSupply.avgSupply;
        maxSupply(s)=outSupply.MaxSupply;
        idxMax(s)=outSupply.idxMaxSupply;
        minSupply(s)=outSupply.MinSupply;
        idxMin(s)=outSupply.idxMinSupply;
        normFF(s)=outSupply.normFFsupply;
        AllHydSupply(s)={outSupply.allSupply};
        FFHydrant(s)={ffdHyd};

        disp(['Completed Segment/Temporary Storage:',num2str(i)])
    else
```

```
        disp(['No sources available or no hydrants present in the
segment, S:',num2str(s)])
        ff=0;
        ffdHyd=0;
        nHydrants=0;
        SumMaxDayDemand=0;
        outSupply=0;


        meanSupply(s)=0;
        maxSupply(s)=0;
        idxMax(s)=0;
        minSupply(s)=0;
        idxMin(s)=0;
        normFF(s)=0;
        AllHydSupply(s)=(ISCO);
        FFHydrant(s)={ffdHyd};
    end

    D_ffd(s)=SumMaxDayDemand;
    %     FireResults(s)={outSupply};
    FF_ffd(s)=ff.*size(ffdHyd,2);


end


%Save workspace variables
exitfilename = [inpname_in,'_firetest.mat'];
save(exitfilename,'D_ffd','FF_ffd','meanSupply','maxSupply','idxMax','i
dxMin','minSupply','normFF','AllHydSupply','FFHydrant');


%save(exitfilename,'D_ffd','FF_ffd','ffdHyd','nHydrants','meanSupply','
maxSupply','idxMax','idxMin','minSupply','normFF','AllHydSupply','FFHyd
rant');


fclose('all');
end
```

```
function [] =FireDemandTest6(inpname_in)
% %Run fire demand metric/test
%  Last updated:05/25/20
% Last modified:06/11/2020
% Compare node pressure to half tank and maximum demand at junction
nodes
% %Load results from segmentation and initial analysis
% % filename=[inpname,'.mat'];%%Name of the file, overwritten for test
% % load (filename); %%Temporarily commented out for test, and
overwitten on next line

load('******_v_av_Hyd.mat','out','out2','NodePressure')
load('******_v_av_Hyd_halfMAX.mat','NodePressure_halfMAX')
```

```
% Run timeSeriesResults_halfMAX.m for pressures at half tank and
maximum
% demand at the end of two hours

nsegments=size(out,2);

AllHydSupply=cell(nsegments,1);
FFHydrant=cell(nsegments,1);

D_ffd=zeros(1,nsegments);
FF_ffd=zeros(1,nsegments);
removed = {out2.removed}.';
removedPIPE = {out2.removedPIPE}.';
inpfn=[inpname_in,'.inp'];
d=epanet(inpfn);
TankResCount=d.getNodeReservoirCount+d.getNodeTankCount;
notskip=zeros(nsegments,1);

notskip=[];
M=2;

TESTNodesHyd2={out2.TESTNodesHyd}';

parfor (s=1:nsegments,M)
    a=s;
    %    %Check which segment is running
    %    disp(a)
    v=0;
    %IndexList=d.getNodeIndex(removed{s,1});
    removedlist=removed{a,1};
    j=num2str(a);
    inpname2=[inpname_in,'_',j,'C.inp'];
    [IndexList,TypeIndex] =
AUXgetNodeIndexandType(inpname2,removedlist);
    IndexCount=numel(TypeIndex(TypeIndex>0));
    nHydrants= size(TESTNodesHyd2{s,1},2); %Cell size of cell 1 by
nHydrants

    if TankResCount>IndexCount
        %Check if hydrants are available
        if nHydrants>0
            v=1;
        end
    end
    exitvariable(s)=v;
end
notskip=find(exitvariable==1);


%Create empty arrays for variables
meanSupply=zeros(1,nsegments);
maxSupply=zeros(1,nsegments);
minSupply=zeros(1,nsegments);

idxMax=zeros(1,nsegments);
idxMin=zeros(1,nsegments);
```

```
normFF=zeros(1,nsegments);

D_ffd=zeros(1,nsegments);

FF_ffd=zeros(1,nsegments);

%Start variables
AllHydSupply=cell(1,nsegments);
FFHydrant=cell(1,nsegments);

idNodes={out2.removed}';
idxFireHydrants={out2.TESTNodesHyd}';
NodePressure2=NodePressure_halfMAX; %Changed to pressures at half
filled tanks,max.pressure,at two hours

parfor (s=1:nsegments,2)

    if ismember(s,notskip)
        i=s;

        s_name=[inpname_in,'_', num2str(i),'C'];
        [ffdHyd,ff,nHydrants,SumMaxDayDemand,outSupply]  =
FireDemand5(s_name,i,idNodes{s,1},idxFireHydrants{s,1},NodePressure2);

        meanSupply(s)=outSupply.avgSupply;
        maxSupply(s)=outSupply.MaxSupply;
        idxMax(s)=outSupply.idxMaxSupply;
        minSupply(s)=outSupply.MinSupply;
        idxMin(s)=outSupply.idxMinSupply;
        normFF(s)=outSupply.normFFsupply;
        AllHydSupply(s)={outSupply.allSupply};
        FFHydrant(s)={ffdHyd};

        disp(['Completed Segment/Temporary Storage:',num2str(i)])
    else
        disp(['No sources available or no hydrants present in the
segment, S:',num2str(s)])
        ff=0;
        ffdHyd=0;
        nHydrants=0;
        SumMaxDayDemand=0;
        outSupply=0;


        meanSupply(s)=0;
        maxSupply(s)=0;
        idxMax(s)=0;
        minSupply(s)=0;
        idxMin(s)=0;
        normFF(s)=0;
        AllHydSupply(s)=(ISCO);
        FFHydrant(s)={ffdHyd};
    end

    D_ffd(s)=SumMaxDayDemand;
    %     FireResults(s)={outSupply};
    FF_ffd(s)=ff.*size(ffdHyd,2);
```

```
end

%Save workspace variables
exitfilename = [inpname_in,'_firetest.mat'];
save(exitfilename,'D_ffd','FF_ffd','meanSupply','maxSupply','idxMax','i
dxMin','minSupply','normFF','AllHydSupply','FFHydrant');

%save(exitfilename,'D_ffd','FF_ffd','ffdHyd','nHydrants','meanSupply','
maxSupply','idxMax','idxMin','minSupply','normFF','AllHydSupply','FFHyd
rant');

fclose('all');
end
```

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VITA

ERIKA HERNANDEZ HERNANDEZ

EDUCATION

Master of Science, Civil Engineering August 2017
University of Kentucky, Lexington, Kentucky

Bachelor of Science, Civil Engineering May 2015
University of New Mexico, Albuquerque, New Mexico

EXPERIENCE

University of Kentucky, Lexington, Kentucky
Kentucky Water Resources Research Institute
Graduate Research Assistant 2015-2020

University of Kentucky, Lexington, Kentucky
Graduate Teaching Assistant: Civil Engineering Department 2016-2020

JOURNAL PUBLICATIONS

1. E. Hernandez Hernandez and L. Ormsbee (2020), "Segment Identification Protocol for Water Distribution Systems" Submitted for publication
2. E. Hernandez Hernandez and L. Ormsbee (2020), "Segment-Based Assessment of The Consequences of Failure on Water Distribution Systems" In press

PEER-REVIEWED CONFERENCE PROCEEDINGS

1. **Hernandez, E.**, and Ormsbee L. (2018) "Application of Segment Based Robustness Assessment for Water Distribution Networks." *1st International WDSA/CCWI 2018*, Kingston, Ontario, Canada.
2. **Hernandez, E.**, and Ormsbee, L. (2017) "Segment Based Reliability Assessment for Water Distribution Systems under Multiple Failure States." *World Environmental and Water Resources Congress*, Sacramento, California.
3. **Hernandez, E.,** and Ormsbee. L. (2016) "Segment-based Reliability Assessment for Water Distribution Systems." *Water Distribution Systems Analysis (WDSA),* Cartagena, Colombia.
4. **Hernandez, E.,** Hoagland, S., & Ormsbee, L. (2016) "Water Distribution Database for Research Applications." *World Environmental and Water Resources Congress,* West Palm Beach, Florida.

CONFERENCE PRESENTATIONS

1. **Hernandez, E.**, and Ormsbee, L. (2019) “Segment Based Criticality Assessment.” *World Environmental and Water Resources Congress*, Pittsburgh, Pennsylvania.
2. Ormsbee, L., Heitzman, G., Evans, S., Hoagland, S. and **Hernandez, E.** (2019) “Key Management Challenges in Operating Small Water Distribution Systems” *KY/TN Water Professionals Conference,* Louisville, Kentucky.
3. **Hernandez, E**. and Mahoney, D.T. (2019) “University of Kentucky Student Chapter Updates” *KY/TN Water Professionals Conference,* Louisville, Kentucky.
4. **Hernandez, E.**, and Ormsbee, L. (2018) “Application of Segment Based Robustness Assessment for Water Distribution Networks.” *1st International WDSA/CCWI,* Kingston, Ontario, Canada.
5. **Hernandez, E.**, and Ormsbee, L. (2018) “Criticality Segment-Based Assessment for Water Distribution Networks” *SHPE Engineering Research Symposium, SHPE Conference*, Cleveland, Ohio.
6. **Hernandez, E.**, and Ormsbee, L. (2017) “Segment Based Reliability Assessment for Water Distribution Systems under Multiple Failure States.” *World Environmental and Water Resources Congress*, Sacramento, California.
7. **Hernandez, E.**, and Ormsbee, L. (2016) “Segment Based Reliability Analysis.” *13th Cincinnati Area Water Distribution Systems Symposium,* Cincinnati, Ohio.
8. **Hernandez, E.**, and Ormsbee, L. (2016) “Segment-based Reliability Assessment for Water Distribution Systems." *Water Distribution Systems Analysis (WDSA),* Cartagena, Colombia.
9. **Hernandez, E.**, Hoagland, S., & Ormsbee, L. (2016) “Water Distribution Database for Research Applications” *World Environmental and Water Resources Congress,* West Palm Beach, Florida.

POSTER PRESENTATIONS

1. **Hernandez, E.**, and Ormsbee, L. (2017) “Segment-Based Reliability Assessment for Water Distribution Systems.” *KY/TN Water Professionals Conference,* Lexington, Kentucky.
2. **Hernandez, E.**, and Ormsbee, L. (2017) “Segment Based Assessment for Water Distribution Systems” *Kentucky Water Resources Research Institute Annual Symposium,* Lexington, Kentucky.

FELLOWSHIPS and AWARDS

Lyman T. Johnson (LTJ) Diversity Fellowship	2017-2020
Outstanding Civil Engineering PhD Student	2020
NSF ACADEME Future Faculty Fellow	2019
Outstanding Civil Engineering PhD Student	2019
AWWA/WEA Kentucky Tennessee Section Scholarship	2016
Timmons Graduate Fellowship in Civil Engineering	2015-2019
Outstanding Engineering Student, New Mexico Society of Professional Engineers-Albuquerque, Engineering week	2015
Outstanding Senior in Civil Engineering, University of New Mexico	2015

School of Engineering Summer Scholarship	2014
International Amigo Transfer Scholarship, University of New Mexico	2014
Registration Fee Exemption Awarded by Academic Excellence, Universidad Nacional de Colombia, Medellin, Colombia.	2010-2012
Academic Excellence Award-100th Anniversary School of Civil Engineering and 125 Anniversary of the Faculty of Mines, Universidad Nacional de Colombia, Medellin, Colombia	2012
National Top 50 ICFES (Colombian standardized test) score	2009
Andres Bello Award for outstanding ICFES score in Mathematics	2009