Scenario-Based Sustainability Assessment to Provide Interactive Decision Support for the Long-Term Transition of Urban Water Supply Systems

Dissertation

Submitted to and approved by the

Faculty of Civil Engineering

University of Kaiserslautern

In candidacy for the degree of a

Doktor-Ingenieur (Dr.-Ing)

By

Nazli Yonca Aydin

Kaiserslautern 2014

(D 386)

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Abstract

This dissertation focuses on the evaluation of technical and environmental sustainability of water distribution systems based on scenario analysis. The decision support system is created to assist in the decision making-process and to visualize the results of the sustainability assessment for current and future populations and scenarios. First, a methodology is developed to assess the technical and environmental sustainability for the current and future water distribution system scenarios. Then, scenarios are produced to evaluate alternative solutions for the current water distribution system as well as future populations and water demand variations. Finally, a decision support system is proposed using a combination of several visualization approaches to increase the data readability and robustness for the sustainability evaluations of the water distribution system.

The technical sustainability of a water distribution system is measured using the sustainability index methodology which is based on the reliability, resiliency and vulnerability performance criteria. Hydraulic efficiency and water quality requirements are represented using the nodal pressure and water age parameters, respectively. The U.S. Environmental Protection Agency EPANET software is used to simulate hydraulic (i.e. nodal pressure) and water quality (i.e. water age) analysis in a case study. In addition, the environmental sustainability of a water network is evaluated using the "total fresh water use" and "total energy intensity" indicators. For each scenario, multi-criteria decision analysis is used to combine technical and environmental sustainability criteria for the study area.

The technical and environmental sustainability assessment methodology is first applied to the baseline scenario (i.e. the current water distribution system). Critical locations where hydraulic efficiency and water quality problems occur in the current system are identified. There are two major scenario options that are considered to increase the sustainability at these critical locations. These scenarios focus on creating alternative systems in order to test and verify the technical and environmental sustainability methodology rather than obtaining the best solution for the current and future water distribution systems. The first scenario is a traditional approach in order to increase the hydraulic efficiency and water quality. This scenario includes using additional network components such as booster pumps, valves etc. The second scenario is based on using reclaimed water supply to meet the non-potable water

demand and fire flow. The fire flow simulation is specifically included in the sustainability assessment since regulations have significant impact on the urban water infrastructure design. Eliminating the fire flow need from potable water distribution systems would assist in saving fresh water resources as well as to reduce detention times.

The decision support system is created to visualize the results of each scenario and to effectively compare these results with each other. The EPANET software is a powerful tool used to conduct hydraulic and water quality analysis but for the decision support system purposes the visualization capabilities are limited. Therefore, in this dissertation, the hydraulic and water quality simulations are completed using EPANET software and the results for each scenario are visualized by combining several visualization techniques in order to provide a better data readability. The first technique introduced here is using small multiple maps instead of the animation technique to visualize the nodal pressure and water age parameters. This technique eliminates the change blindness and provides easy comparison of time steps. In addition, a procedure is proposed to aggregate the nodes along the edges in order to simplify the water network. A circle view technique is used to visualize two values of a single parameter (i.e. the nodal pressure or water age). The third approach is based on fitting the water network into a grid representation which assists in eliminating the irregular geographic distribution of the nodes and improves the visibility of each circle view. Finally, a prototype for an interactive decision support tool is proposed for the current population and water demand scenarios. Interactive tools enable analyzing of the aggregated nodes and provide information about the results of each of the current water distribution scenarios.

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List of Abbreviations

DSS   Decision support system

EPS   Extended period simulation

GIS   Geographic information system

GPD   Gallons per day

GPM   Gallons per minute

MCDA Multi-criteria decision analysis

PVC   Polyvinylchloride

REL   Reliability

RES   Resiliency

SI   Sustainability index

SSA   Steady state analysis

WDS   Water distribution system

VUL   Vulnerability

Unit Conversion Table

PARAMETER	US CUSTOMARY	SI METRIC
Length	1 foot	$\cong$ 0.3 meter
	1 inch	25.4 millimeter
Pressure	1 psi	$\cong$ 0.7 mH_2O
Flow	1 gallon	$\cong$ 3.79 liter
	1 gallons per minute	$\cong$ 0.004 m^3/min

CHAPTER 1

INTRODUCTION

1.1 Background

Sustainable water resource management activities are escalating around the world as well as the search for alternative solutions for water stress due to population increase and demographics. Several researchers, water research institutions and governments have proposed sustainability criteria for the water resources sustainability in order to assess water supply strategies. However, quantifying the sustainability of the urban water resources is a very challenging problem since sustainability is difficult to define and a rather vague concept.

Clear definitions, goals, time and space scales are needed together with the quantifiable indicators in order to assess sustainability (Kay 2000). One approach was proposed by Hashimoto et al. (1982) using reliability, resiliency and vulnerability performance indices to measure the behavior of the water resources with respect to predetermined thresholds representing satisfactory conditions. Loucks (1997) introduced the concept of Sustainability Index (SI) calculation using these performance criteria together as a tool to quantify and monitor sustainability over time. Once the desired satisfactory conditions are determined in terms of sustainability, this approach may assist in the comparison of alternative future scenarios in the water resources management field.

Scenario development is a tool for planning, which originated in the late 1960s and has been used since then to illustrate alternative visions of the future under several assumptions (Thomas 1994). The main focus of scenario development is not forecasting or predicting, but rather exploring various paths to the future. The scenario analysis tool can assess possible future outcomes of short term or long-term policies and decisions that are performed. Using scenario analysis can fill the gap between scientific studies and decision makers. System vulnerability and adaptation

measures can be explored through the scenario analysis based on stakeholder or decision makers' goal for future conditions. Creating applicable and credible scenarios, setting the driving forces and scenario objectives are the crucial factors to achieve the desirable future conditions. Baseline conditions should be investigated throughout in order to convince the decision makers to take an action to revise the current condition. Once decision makers and stakeholders set the objectives for the future, scenarios can be narrowed down according to the scope of the process.

Ni et al. (2012) proposed four different water resources sustainability scenarios based on increasing water demand in order to assess the water resource availability by 2020 on Chongming Island. Willuweit and O'Sullivan (2013) focused on urbanization and climate change scenarios and created a decision support system (DSS) in order to assess the performance of centralized and decentralized water management alternatives. Weng et al. (2010) used multi objective optimization and scenario analysis in order to assess the impacts of different water resources management policies in the Haihe River Basin, China.

The main challenge in urban water resources sustainability is centered on meeting water demands with the available water resources that are insufficient in most urban areas. Specifically developing countries are struggling with the uneven distribution of the existing water resources and the infrastructure requirements to allocate water in the rural areas as well as urbanized regions. On the other hand, in developed countries, water quality and/or fire flow regulations are forcing water service providers to store and provide high quality water in urban areas as well as in rural settlements. In order to meet the water quality and fire flow regulations, extensive centralized water distribution infrastructures are used to move water from water treatment facilities to rural settlements, which require extensive infrastructure, and operation and maintenance costs.

Even though centralized water distribution systems (WDSs) were considered as solutions in the early 1900s in most of the developed countries, currently, disadvantages of these are widely reflected by researchers. For example, one drawback of a centralized urban WDS is that the population in urban areas is increasing while the rural population is decreasing due to the migration and declining national birth rates in developed countries. The centralized water and wastewater infrastructure investments together with the operation and maintenance costs for rural areas may not be feasible for decreasing future rural water demand. In contrast, increasing water demand in urban areas will require effective decision-making policies with respect to asset investments. Water supply providers need to satisfy the water demand of all customers at an acceptable cost while protecting the natural resources for sustainable development (Ashley et al. 2004). Therefore, secure and sustainable water supply will be a major challenge in the future for water utilities. Currently, an effort for finding an alternative water resource has already been started and focused on decentralized or satellite water – wastewater systems using rainwater harvesting or reclaimed water as alternative resources. These

applications require separate water networks so called dual WDSs in order to provide reclaimed water to the communities.

Providing a sustainable urban WDS is a complex process involving decision makers, authorities as well as public opinion. In order to achieve sustainable water resources management, long term consequences of the water uses need to be identified together with the tradeoffs between the current and future water demand and water availability for the sake of future generations (Cai et al. 2002). Evaluation of alternative concepts and showing the different options to achieve sustainability are significant steps in the decision-making procedure. In this process, it is important to illustrate the options to decision makers and make them fully understand the reasoning as well as cause and effects of each policy that has been proposed to improve the sustainability of the current and future water resources scenarios.

A successful visualization to aid decision makers is a must-have tool in order to demonstrate these scenarios and their implications. Decision makers should be able to investigate and even influence the alternatives of each scenario. Visual representation of the water network will assist decision makers to identify problematic regions and to provide alternative solutions for sustainable water resources. Visualization tools and DSSs will improve the effectiveness of the whole decision process by incorporating data and knowledge.

1.2 Problem statement

The first problem addressed by this research is to assess the environmental and technical sustainability of a centralized urban WDS based on alternative scenarios. Then, the current and future population and water demand scenarios are investigated considering transition from a centralized urban WDS to a decentralized urban WDS. In addition, the feasibility of using a reclaimed water supply for fire flow is investigated for each current and future population and water demand scenarios. Finally, in order to provide an effective DSS for the stakeholders and decision makers, several visualization techniques are used together to illustrate each scenario. For the current population and water demand scenarios, interaction tools are integrated into the DSS in order to facilitate the scenario comparison for the decision making process.

1.2.1 Population and water demand

As mentioned before, the sustainability of urban WDSs is confronted with the problem of meeting the future demand using existing water supplies. The population is increasing in metropolitan regions such as in Arizona, New Mexico, and Florida (Natural Resources Defense Council 2010), while rural area populations are decreasing in developed countries due to the migration rates and reduced birth rates.

For example, in Germany, the population is expected to decrease approximately 14 % by 2050 (Federal statistical office 2006). The problem associated with the current urban WDS is to provide water to remote communities by meeting the water quality and fire flow requirements. In this dissertation, the problems of decreasing rural population and increasing population in cities are addressed in the future population and water demand scenarios, specifically shifting from a centralized to a decentralized urban WDS are investigated in terms of the environmental and technical sustainability.

1.2.2 Sustainability of centralized water distribution systems

The sustainability of centralized WDSs has already been questioned due to pumping energy requirements, water losses due to pipe leakages, and operation and maintenance costs of piping and pumping systems. In addition, new emerging problems with water availability are forcing authorities to save as much water as possible. From the technical sustainability perspective, providing water to remote communities (i.e. moving water long distances) requires high-pressure operations, which results in loss of fresh water resources due to possible bursts in pipes. Storing water in these remote communities due to fire flow requirements is causing water quality deterioration (Asano et al. 2007). In some regions, water utilities have to flush water, which stays in the pipes for such a period that the water quality deteriorates. Therefore, authorities are faced with the problem on one hand of providing water to communities for safety and living purposes and on the other hand of diminishing fresh water resources, which is one of the most valuable assets for countries worldwide.

The sustainable urban water infrastructure can be provided with effective urban water management activities. The challenge is to identify realistic and probable scenarios and to illustrate the outcomes of each scenario, which would assist decision makers in achieving sustainable solutions for the current and future urban water infrastructures. Each scenario should have a rationale for the proposed changes and illustrate the consequences and results implicitly. Most importantly, baseline situations and problems need to be identified properly in order to convince decision makers and stakeholders of the future alternatives and changes.

Each alternative scenario is subject to changes in spatial and temporal properties and accordingly will result in changes in the urban WDS. These changes should be clear for decision makers to understand the concepts and the rationale of each scenario. In this process, visualization of possible future options will aid decision makers and stakeholders. The Visualization will illustrate the current problems and the outcomes of the proposed solutions.

1.2.3 Visualizing water networks

Traditional urban water distribution visualization includes the nodes and pipes of the network. Nodes are not necessarily evenly distributed and results in overlaps in some regions and scarce in other areas of the network. This may confuse decision makers and keep them from seeing the problem if the nodes and the pipes are not completely visible. The Animation technique is the most commonly used approach to visualize nodal pressures and water ages in the urban WDS for an extended period of time. Although animation is very useful in terms of illustrating the fluctuation in chosen parameters, simultaneous and temporal changes may cause change blindness and result in loss of information needed for decision makers (Nowell et al. 2001).

1.3 Research objective and phases of research

The research objective of this dissertation is to develop a methodology for investigating the technical and environmental sustainability of centralized urban WDSs that consider both current and future population and water demand scenarios. In this dissertation, the sustainability of the current water infrastructure is evaluated based on the technical and environmental criteria. While the environmental criteria are limited to the energy intensity and total fresh water use, the technical sustainability is evaluated based on the hydraulic efficiency (i.e. nodal pressure) and water quality (i.e. water age).

The proposed methodology defining the technical and environmental sustainability of WDS is first applied to an existing water distribution network. This network has the properties of a centralized WDS. Two reservoirs supply the water demand area at a distant location, which produces water quality and hydraulic efficiency problems.

The main goals of this dissertation are:

- Developing a methodology to assess the technical and environmental sustainability of an urban WDS.

- Identifying the problems in a centralized water network with respect to the proposed technical sustainability assessment.

- Building scenarios for the identified problems in an existing centralized water network.

- Considering a traditional approach as well as decentralization of the water infrastructure options in order to increase the sustainability of the urban WDS for the current system scenarios.

- Evaluating the technical and environmental sustainability of an existing urban water infrastructure in terms of the proposed current population and water demand scenarios.

- Investigating the water network sustainability under several population and water demand assumptions. First, population and water demand decrease through the water network is investigated in order to represent the population and water demand decrease in rural areas in the most developed countries. Second, the population and water demand increase which is a common problem threating sustainability of the water supply in the most of the countries around the world.

- Using visualization techniques to address the scope of each current and future population and water demand scenarios and their impacts on urban water distribution networks.

- Creating an interactive DSS in order to provide a comparison tool for the current population and water demand scenarios.

The research phases for this dissertation are provided in Figure 1.1.

Phase 1

As the first phase of this research, a technical sustainability assessment is defined for the water network using the parameters of hydraulic efficiency and water quality. Loucks (1997) introduced the SI calculation using resiliency, reliability and vulnerability performance criteria, which were defined by Hashimoto et al. (1982). He suggested using reliability, resiliency, and vulnerability tools together to quantify and monitor sustainability over time. Sandoval-Solis et al. (2011) improved the structure and dimension of the SI calculation proposed by Loucks (1997) in order to compare alternative water management policies in the Rio Grande Basin. The above application focuses on water supply defining a deficit on the basis of whether the supply in terms of volume can be satisfied. In this dissertation, the SI based upon the water quality (i.e. water age) and the hydraulic efficiency (i.e. nodal pressures) is developed and applied to assess the technical sustainability of a WDS. Water age together with the nodal pressure is the parameters chosen to define the water supply sustainability of current and future systems. In addition, the environmental sustainability criteria are proposed for the urban water infrastructure. The total fresh water use and the energy intensity for each scenario are identified as environmental sustainability criteria.

Phase 2

The second phase of this dissertation is to analyze a water distribution network with current water demand in terms of sustainability using the methodology developed in Phase 1. The main reason for investigating the existing water network is to analyze the effects of centralized WDSs with current water demand on sustainability.
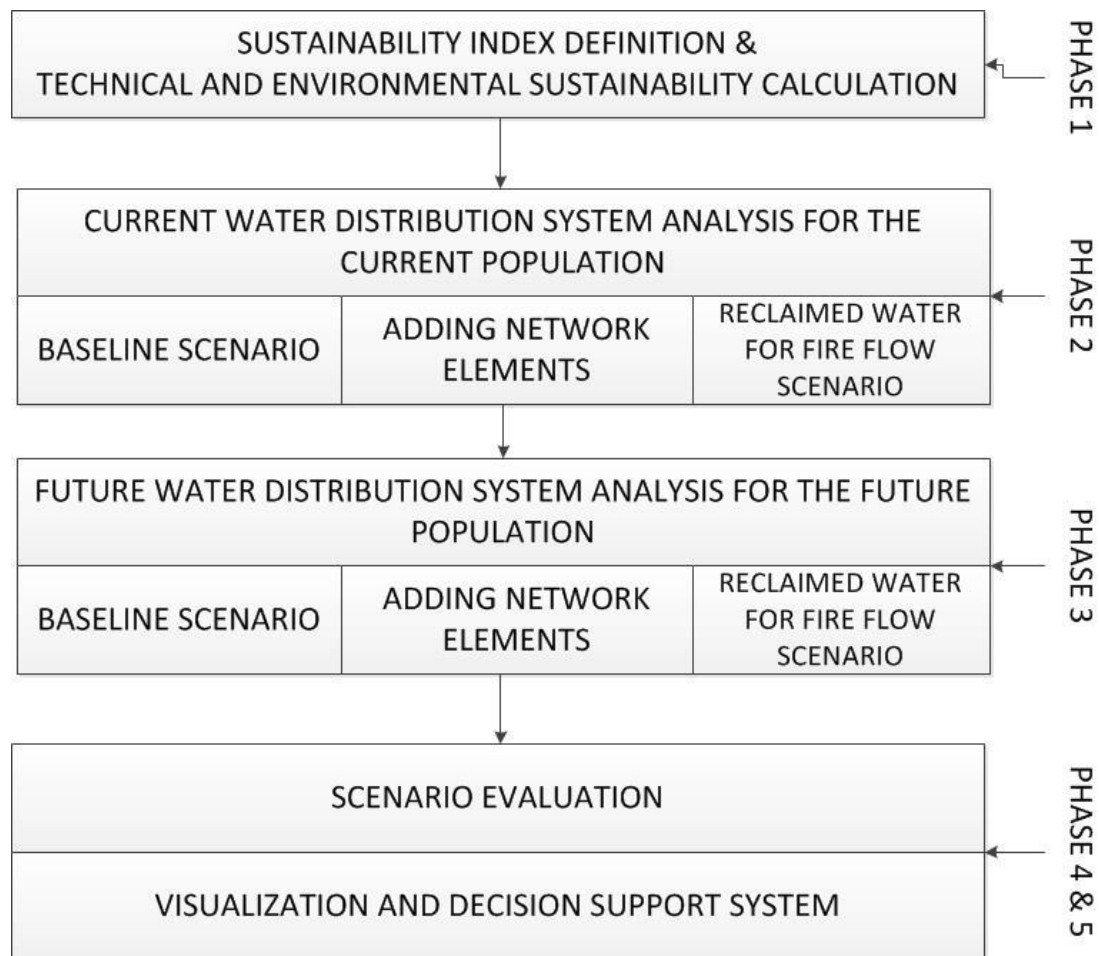
Figure 1.1 Main phases of the thesis

The problematic regions are identified, alternative solutions are proposed and the impacts of these solutions are evaluated with the proposed technical and environmental sustainability assessment methodology. For this phase, in addition to baseline conditions, two more approaches are recommended. First, a rather traditional approach is considered by adding new network elements in order to increase the sustainability indices in the network. Second, decentralization of the current system is suggested for the problematic regions. Fire flow, toilet flushing and irrigation demands are met using the dual WDS, so that the existing water network can serve potable water. A dual water distribution network is designed and the sustainability of the dual system is investigated. The goal of this phase is not designing a WDS that fully satisfies the sustainability objectives but to test and verify the feasibility of proposed solutions based on the sustainability methodology.

Phase 3

The third phase is to investigate the different future water demands and sustainability conditions of the existing system. This reflects the population and demand changes in the future and how these parameters would affect the future water supply infrastructure. The water demand is examined first for the increased

water demand in metropolitan areas and then for the decreased water demand in rural areas. For decreased demand conditions, a baseline condition without any modification to the infrastructure is investigated and new network elements are added to follow the traditional approach as one scenario. The third scenario is to remove the fire flow from the existing system and adding the dual water network for fire flow, irrigation and toilet flushing.

Phase 4

The effects of the proposed current and future scenarios are examined in this phase. Scenario analysis is conducted in order to evaluate the alternatives and the best possible solution for the future. In this phase, current water demand scenarios and effects of increase and decrease of population on water distribution network are investigated in terms of the proposed environmental and technical sustainability assessment methodology. In Phase 2, current problems are identified and the solutions are proposed to improve the technical sustainability. In addition, fluctuations in the future urban water demand and population effects are handled in each scenario in Phase 3. However, Phase 4 gives an insight into those solutions by considering advantages and disadvantages of each phase and corresponding scenarios. Therefore, in order to compare the feasibility of each current and future population and water demand scenarios, environmental and technical sustainability criteria are aggregated into an overall score. Several weighting options for each criterion are considered to reflect the decision maker's preferences. In this phase, the possible pathways from the current system to the future are investigated.

Phase 5

The final phase is to visualize the scenarios in order to assist decision makers in comparing the outcomes of each scenario. The U.S. Environmental Protection Agency EPANET software is utilized in order to model an urban water distribution network as a function of operation time (Rossman 2000). Even though the EPANET software is a useful tool to conduct hydraulic and the water quality analyses, the visualization capability of the EPANET software is rather limited for decision support purposes. Therefore, in this phase, the EPANET simulation results for each scenario are represented using several visualization techniques in order to achieve a better visual representation of an urban WDS. The first visualization technique used in this dissertation is called small multiple maps. This method assists in overcoming the problem of change blindness due to an animation that is widely used especially in hydraulic and water quality simulations. A second visualization technique is used to simplify the network nodes, which are densely populated in some regions of the existing water distribution network and sparse in other areas. The simplification reduces the overlapping nodes in dense regions therefore allows decision makers to view each node individually. The circle view technique (Keim et al. 2004) is used to represent multiple values of each variable (i.e. water age and nodal pressure) at each node. Finally, in the third approach, the network is fitted into a grid representation to

eliminate the irregular geographical distribution of the nodes. In order to further improve the usability, interaction tools are designed in this dissertation for the current population and water demand scenarios. This interactive DSS provides an easy comparison tool and illustrates the results of the environmental and technical criteria for each current system scenario.

1.4   Contributions and limitations

A methodology is developed for investigating the technical and environmental sustainability of centralized urban WDSs that considers both current and future populations and water demand scenarios. Reliability, resiliency and vulnerability performance criteria are used to quantitatively define the technical sustainability for the urban WDS. In addition, total fresh water use and energy intensity are considered as environmental sustainability criteria. Scenarios are developed in order to assist decision makers for considering transitions from centralized to decentralized WDSs.

The technical sustainability methodology developed herein is a credible approach to identify problematic regions in water supply networks.

The proposed methodology may assist in improving water services and compare different WDS scenarios in terms of technical and environmental sustainability.

Scenarios are created considering traditional problem solving techniques used in the urban water network and more innovative approaches such as using reclaimed water as an alternative resource.

As a part of the current and future scenarios, the possibility of eliminating fire flow from a potable distribution system is investigated. Using reclaimed water for fire flow purposes has limited real world examples. Storage and infrastructure requirements of fire flow in current urban water networks are causing water quality deterioration and loss of water supply. In this dissertation, this problem is addressed and a dual WDS is proposed as an option. In addition, sustainability of the dual distribution network is investigated using water age and nodal pressure variables as well as environmental criteria (i.e. fresh water use, energy intensity).

Existing visualization techniques are modified and adapted in order to illustrate each scenario. The proposed visualization method assists decision makers to understand the reasoning, cause and effect relationships of each option. The interactive DSS increases the efficiency of identifying the problematic locations. Comparing time series line charts and the sustainability evaluation results for each scenario facilitates the decision making process.

One limitation of this dissertation is that the sustainability of urban WDS is analyzed in terms of the technical (i.e. water age and nodal pressure) and environmental

criteria. However, economic and social criteria to evaluate the sustainability are eliminated due to limited available data.

In addition, future population increase and decrease scenarios are assessed based on these assumptions. The examples for the population and water demand increase (i.e. Arizona, USA) and the population and water demand decrease (i.e. Kaiserslautern, Germany) are investigated in order to build future scenarios. In this dissertation, the urban development and expansion are neglected.

The proposed interactive DSS is limited to this study area and to the current population and water demand scenarios. As this decision support tool is a prototype, the future population and water demand scenarios have not been incorporated into the tool.

1.5   Organization of dissertation

This thesis is comprised of eight chapters describing the research work performed and the results. A literature review related to sustainable water resources is presented in Chapter 2. The review specifically emphasizes sustainable WDSs, potable and non-potable WDS models, urban water management, and DSSs. The concepts of reliability, resiliency and vulnerability are also explained together with scenario analysis and evaluation.

In Chapter 3, materials and data types used in this study are defined in detail. The description of the study area and details of data processing are provided. Software packages such as EPANET, ArcGIS, GAMS and Excel tools used in this study are described in detail as well.

Chapter 4 describes the technical and environmental sustainability assessment methodology developed for WDSs together with the scenario building and evaluation steps. The mathematical tools to describe reliability, resiliency and vulnerability as well as design requirements for dual WDSs and a linear programming optimization model are also discussed in this chapter.

Chapter 5 demonstrates the new methodology developed for visualizing time-dependent variables of WDSs. Existing methodologies using the circle view approach and small and multiple maps are discussed together with aggregating network edges and schematizing the water network. In addition, the interactive DSS design properties are explained in detail in this chapter.

Chapter 6 and 7 demonstrate the implementation of the proposed methodology on an existing water distribution network considering both current and future population and water demand scenarios.

Chapter 8, the final chapter of this dissertation summarizes this research together with conclusions and limitations as well as recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Sustainable development and water resources sustainability

The sustainable development concept was first recognized in the Brundtland Commission's report of Our Common Future (1987) and defined as meeting the needs of current generations without compromising the ability of future generations to meet their own needs. It is clear that the foremost feature of sustainable development is to acknowledge the needs of future generations. The sustainable development concept is first considered as an ecological or natural notion and applied to measure and achieve desired environmental targets. However, social scientists and economists argue that the achieving sustainable development targets should not be based on only ecological-environmental criteria but economic and social targets should be part of the decision process (de Vries and Petersen 2009).

Since the Brundtland Commission report (1987) introduced the sustainable development concept, many researchers from different disciplines have been trying to define, assess and adapt sustainable development targets (Loucks 1997). Loucks (1997) discussed the issues and challenges of providing sustainable development. He stated that the main challenge of achieving sustainable development is in identifying a level of tradeoff between current and future generation needs. How much non-renewable natural resources current generation could/should preserve for a future generation? Consuming environmental and economic assets could provide higher standards of living and eventually induce improvements in technology and knowledge for the current generation. This would enable future generations to discover more advanced technological innovations that would use less natural, environmental and ecological resources. Although this scenario might not be realistic, it is necessary to all single uncertainties while providing sustainable development.

The challenges of achieving sustainable development are also considered by Rijsberman and Van de Ven (2000). They stated that the main challenge is the complexity of the sustainability problem which involves environmental, economic and social aspects. Evaluating, comparing or scoring the tradeoffs between these aspects is difficult. Another challenge is that the solutions affect a large number of stakeholders or governments who have dynamic and different objectives that are changing over time. Time scale brings the uncertainties which cannot be eliminated due to the complexity of the problem. Therefore, stakeholder interaction is necessary. Although it is possible that the proposed solutions may not be acknowledged by a certain group of stakeholders, it is important to ensure that the stakeholders or certain groups do not obstruct in the reach for the sustainability objective.

As there is no common definition of sustainable development, water resources sustainability is defined by several researchers differently. Loucks and Gladwell (1999) defined sustainable water resources systems as designing and managing water resources to satisfy the objectives of the current and future generations while maintaining the ecological, environmental and hydrological integrity. Mays (2007) defined water resources sustainability as "the ability to use water in sufficient quantity and quality from the local and global scale to meet the needs of humans and environmental ecosystem for the present and future to sustain life, and to protect humans from the damages brought about by natural and human-caused disasters that affect sustaining life" (Mays 2007).

Sustainability by definition enforces decision makers to consider not only current populations but future generations as well. The current problem with sustainable water resources is that limited fresh water resources are distributed unevenly around the world and in some developing countries; part of the population still does not have access to safe drinking water. Consequently, water demand and supply management are very important in order to prevent renewable fresh water resources degradation (Loucks and Gladwell 1999). In the last decade, developing and developed countries around the world have also been dealing with water stress due to internal and external factors such as increasing population, climate change, increasing industrial and residential water usage and declining water availability (Flint 2004).

2.1.1 Population

According to the World Bank report (2004), the population around the world is expected to increase; in its projection, around 2.5 billion more people will live on earth by 2030 and 90% of this population is expected to be in developing countries. Currently, 84% of the worlds' population living in developing countries is expected to reach 88%. On the other hand, developed countries already have slower population growth rates due to the stabilized birth rates and increasing death rates as a result of aging population. Italy and Germany are facing natural population

decrease rates and soon Japan and Spain are predicted to as well. The problem with population increase in developing countries is that there are already limited amounts of economic and natural resources available to the current population which is expected to be less per capita in the future. In addition, it is expected that the population growth specifically between 2000 and 2030, will occur within urban areas in the developing countries while the overall rural population is expected to decrease gradually (UNESCO, 2006). In developing countries, increasing population in urban areas will bring problems of housing, infrastructure, declining sanitation, environmental pollution and inadequate water supply (UNESCO 2009).

2.1.2 Climate change

Climate change distresses water resources by changing water storage patterns through the hydrological cycle. Changing temperatures result in shorter spring snowmelt, and increasing winter runoff therefore completely changing the overall seasonal stream flow pattern (Mays 2007). Olmstead (2013) stated that climate change may affect the availability of water resources in the long-term as well as short term water variability. UNESCO (2009) report listed the effects of climate change on water resources sustainability and management. One challenge that water managers face due to climate change, is that the long-term plans and water system designs can no longer be based on historical data set due to the extreme changes in seasonal patterns. Climate variability is also affecting economic growth due to the uncertainty and unpredictability of long term investments specifically infrastructure design.

Climate change and hydrologic cycle have been studied extensively and several models have been developed by researchers. For example, Raje and Mujumdar (2010) studied climate change impacts on reservoir performance in Hirakud reservoir on the Mahanadi River in Orissa, India. Performance criteria are identified in terms of reliability, resiliency, vulnerability and deficit ratio of hydropower. Here a General Circulation Model was used to evaluate hydrologic scenarios and climate change adaptation policy for reservoir operation was estimated using stochastic dynamic programming. The results showed that the hydropower generation reliability was decreasing in most scenarios. Jyrkama and Sykes (2007) investigated the spatial and temporal changes of groundwater recharge with respect to changing climatic conditions. Future estimation of hydrologic cycle is simulated using 40 years of weather data in the Grand River watershed. Results show that groundwater recharge will increase due to the climate change. Precipitation will occur frequently and in high intensity which will contribute to surface runoff. The study concludes that climate change may have significant spatial variability. Ficklin et al. (2009) applied climate change sensitivity analysis in an agricultural watershed. The Soil and Water Assessment Tool was used for hydrological modeling and climate change impacts in San Joaquin watershed in California. Results of the study indicates that the atmospheric CO_2 concentration together with changes in temperature and

precipitation have adverse impacts on water yield, evapotranspiration, irrigation water use and stream flow.

Hydrologic cycle and water resources are linked to climate change. As climate changes around the world, water quality and quantity will continue to change accordingly. Trenberth (2011) emphasized that climate change might lead to extreme weather conditions, in other words, dealing with alternating droughts and floods annually. This condition will trigger water management challenges such as storing excess water in times of flooding to be used during times of drought. Climate change impacts on the water use patterns in urban scale are investigated by Guhathakurta and Gober (2007). They stated that the increased temperatures and droughts as well as low precipitation resulted in increased residential water use per capita in the Phoenix metropolitan area. House-Peters and Chang (2011) investigated climate change effects on residential water consumption. Their calculations indicated that a 3 degree of temperature change in August could increase the water consumption per house hold by 4061 liters.

Water stress due to climate change is already long-established in some parts of the world and expected to increase in the future. Climate change has and will have various impacts on water resources including reduced water supply availability (Jenerette and Larsen 2006). Olmstead (2013) stated that the water institutions and decision makers should manage water supply and demand considering climate change impacts. Water conserving technologies (i.e. low-flow toilets) and mandatory water use restrictions could assist in the limiting of water uses. These demand management factors would contribute to secure the water supply as well as decrease the water related impacts of climate change.

2.1.3 Water use

Cities are becoming more concentrated areas due to population growth which directly affects the water use in the metropolitan areas. In some parts of the world, the water use per capita is increasing substantially with the population. However this growth trend depends on the social and physical dynamics of the locations (Alcamo et al. 2003). Global water use has been increased three times in the last 50 years. Although population growth is a great contributing factor to increased global water use, changes in lifestyles, technology, international trade and the expansion of water supply systems are also contributing factors (Gössling et al. 2012). Increasing need of water is leading to over abstraction of groundwater uses, specifically in areas where the surface water is not available. Groundwater exploitation results in water quality deterioration and land subsidence (UNESCO 2012). Approximately 42 % of groundwater wells in Europe, which are used for industrial and domestic water consumption, suffer from salt water intrusion (Chiramba 2010).

The global water demand is expected to increase 55% by 2050 primarily due to manufacturing, electricity generation and domestic use of water (OECD 2012). According to the UNESCO report (2009), agricultural activities will be one of the most contributing factors in the future water consumption increase. Approximately, 70 % of urban water withdrawal is for agricultural use. On the other hand, approximately 20 % of the global freshwater use is for industrial uses. These also vary based on the countries income levels. For example, low income countries water consumption for industry is about 5 % while this can go up to 40% in the high income countries which indicate that there is a strong relationship between industrial water use and economic development levels. The water quality requirements for most of the industries are low except pharmaceutical and high technology industries. This enables the use of recycled or reclaimed water for industrial purposes.

Domestic water use is about 10 % of the global freshwater withdrawal. While domestic water use (i.e. residential water consumption) is not a large proportion of the global water withdrawals, only a small percentage of that water demand is used for drinking water and the rest is used for outdoor irrigation and indoor non potable water. Makropoulos et al. (2008) stated that approximately 15-20 % of indoor water demand is necessary for drinking water purposes. The rest of the domestic water demand could be substituted with reclaimed water. In addition, water efficient appliances could provide fresh water savings in residential areas. Details of residential water use will be discusses in the sustainable urban water management section.

2.1.4 Other factors affecting the water resources sustainability (Unsustainable Water)

Extreme changes in population will result in increasing water demand especially in urban areas. This situation will accentuate with migration from rural to urban areas. Higher living standards and economic development will also increase the demand for water supply (UNESCO 2012). On the other hand, fresh water supply is not distributed evenly on earth or based on the population of the earth. Some regions may have redundant resources with respect to the population or vice versa (Loucks and Gladwell 1999). These issues will challenge water managers to explore alternative water management strategies and alternative water supplies.

Issues of sustainable water supply use for rural areas have been discussed by researchers. Sun et al. (2010) stated that the main issue of providing drinking water supply to rural areas is that of institutional barriers. Water institutes must provide, manage and maintain the sustainable use of water. In rural areas where the water infrastructure is not available, people are forced to store water supplies in their homes for long term periods which, in the past have resulted in water borne diseases. Providing or sustaining household scale water treatment and storage facilities would definitely reduce water related diseases in developing and developed countries

(UNESCO 2012). Madrigal-Ballestero (2012) stated that the major challenge in providing water to rural communities is to provide the infrastructure. Decentralizing the institutions and creating local policies would assist to achieve and maintain sustainable water infrastructures over time.

Water infrastructure requires a certain investment and therefore should be protected since it is an important component to provide and ensure safe drinking water to communities. Although transporting water from source to treatment plants and then to the consumption points are extremely important, the operation and maintenance of water distribution and storage systems are neglected in most regions around the world. This results in increasing water losses, and risk of bursts and leakages which could lead to drinking water contamination and public health problems (UNESCO 2012). A WDS requires funding for renewing or rehabilitating the drinking and wastewater infrastructure systems. Even in developed countries, this funding could be a substantial amount and is usually overseen. For example, Olson et al. (2003) stated that 19 cities in the USA require rehabilitation of WDS with regards to aged plumping systems that effects the drinking water quality and could cause public health risks. This situation is of course much worse in developing countries. While some regions in developing countries do not even have a water infrastructure system, where it is available, water providers are faced with financial problems, poor performances, high levels of unaccounted for water and low water pricing. Safe and effective urban water supply and sanitation systems together with the efficiency in service provisions are very crucial to provide sustainable water services. These issues are accentuating the importance of sustainable urban water management.

2.2 Sustainable urban water management

Water stress is increasingly compelling authorities to employ effective and sustainable urban water management strategies. In urban areas, water has to be managed for residential, commercial, industrial and irrigation uses as well as for maintaining local environments such as urban streams. For these reasons, storm water must also be collected and managed to prevent any environmental and economic damage (Daigger 2011). Before the concept of sustainable water management and the factors leading to water stress, water management was very straightforward for governments and authorities. A single and centralized water infrastructure was used to meet water demand which was costly but effective. However, decreasing water availability and increasing population call attention to the need for new water management strategies (Daigger 2007).

Traditional urban water management steps consist of the collection of water supply in order to meet the demand, treatment of the collected water to achieve standard water quality, and delivering the water to end users. Due to the unavailability of local water supply meeting water demand in urban areas, they highly depended on importing/transporting water supply from remote areas. This transportation was

costly not only for the required infrastructure but also the energy required for pumping. In retrospect, this energy cost was insignificant considering at the time the energy was inexpensive and the water delivered to the customers was inexpensive as well. The authorities focused on delivering water but not managing the consumption or promoting efficient use of water (Daigger 2011).

On the other hand, today, sustainable urban water management approaches include using local water supply such as rainwater and reclaimed wastewater. Used water previously seen as "waste" collected and treated according to the purpose of use and today reused in order to achieve enhancing water supply. Wastewater treatment technologies have evolved and enabled treating the wastewater for the purpose of use (Daigger 2003, 2008). In urban regions, there are many demands that do not require meeting potable water quality requirements including landscape irrigation, industrial water demand, groundwater recharge, recreational purposes, surface water augmentation (Gikas and Tchobanoglous 2009). In fact, a very small proportion of the water demand per person, approximately 40 Liters/capita-day, is required solely for direct water consumption like drinking and cooking. The non-potable water demand could range in between 100 to 400 liter/capita-day which is used for laundry, toilet flushing, bathing and outdoor irrigation (Daigger 2011).

Innovations in water treatment technologies are enabling the use of local water resources through centralized and decentralized or hybrid systems (Daigger 2011). These systems require a substantial capital investment. In addition, transporting water resources from remote areas into the service area requires extensive energy cost. On the other hand, distributing and treating local water resources (i.e. waste water, rainwater etc.) requires separate non-potable WDSs which would eventually assist to reduction in size of potable WDS. Needless to say, using local resources would reduce the energy cost of pumping water from remote areas. In addition, water resource enhancement and diversification would enhance the water security as well as reduce the amount of water extracted from natural resources (Marlow et al. 2013).

Transition from centralized to decentralize (i.e. a separate non potable water networks) within the infrastructure perspective is discussed by Marlow et al. (2013). Centralized WDSs in developed countries have been around and practical for many decades. These infrastructures have a life span of many years but were built in different times and rehabilitation of these assets is being dealt with piece by piece whenever needed with the same centralized approach. Therefore, there is a loop of centralized infrastructure and radical changes from centralized to decentralized systems are rather unrealistic. Introducing new infrastructure gradually and adapting innovative technologies whenever a new investment is needed as Marlow et al. (2013) calls "system hybridization" is one way to practice sustainable urban water management.

Transitions from centralized to de-centralized or hybrid water infrastructures have a wide range of applications in literature. Sapkota et al. (2013) proposed a framework to assess the efficiency of hybrid water supply systems based on the volume, peak flow and water quality of wastewater and storm water as well as the reliability of hybrid water supply systems. In order to assess hybrid water supply systems, several modeling approaches were combined (i.e. water balance modeling, contaminant balance modeling, multi-criteria decision analysis (MCDA), and uncertainty analysis). While this research was proposed to assess the impacts of hybrid systems on wastewater and storm water quality and quantity, the framework did not include the cost of hybrid systems and energy usage as well as social perception towards using hybrid systems.

Sharma et al. (2009) evaluated urban water services with respect to environmental and economic sustainability assessment criteria. While life cycle assessment of an urban infrastructure system was considered as the economic criteria, water, wastewater and storm water quantity and quality as well as greenhouse gas emission production due to energy usage in the urban infrastructure were used as environmental criteria. Several scenarios were developed to assess urban infrastructure alternatives in Melbourne, Australia. They have concluded that a significant amount of freshwater resources could be saved using alternative resources applications (i.e. wastewater recycling) as well as demand management strategies. Mitchell (2006) reviewed the implementation of integrated urban water management approaches in the Australian water industry. The review study showed that the integrated urban water management applications have a variety of contributions to total urban water cycle. Mitchell (2006) stated that practicing integrated urban water management to improve urban water cycle (i.e. combining water supply, storm water and wastewater components) could assist in achieving sustainable urban water systems. Water recycling, improving water efficiency and practicing water sensitive storm water management were defined as tools that needed to be integrated into water systems in sustainable urban communities.

Fattahi and Fayyaz (2010) proposed a mathematical model for integrated urban water management. Integrated urban water management was defined for a technical assessment of water services. Instead of planning sanitation, waste disposal, urban storm and runoff, water reticulation individually, interaction between water services and urban systems should be considered for an integrated management. This could also overcome the issues of cooperation between these services. Foxon et al. (2000) studied urban water supply and wastewater system sustainability with respect to water demand management. The main purpose was to create different scenarios to achieve a sustainable system. Grey water recycling, leakage reduction, compulsory metering, and toilet conversion (i.e. using efficient water fixtures) were considered as alternative water management strategies. Results showed that different demand measures could provide water efficiency and save the freshwater that was entering the system. Makropoulos and Butler (2010) investigated sustainability of the

distributed water infrastructure in terms of water supply, wastewater and drainage. Both centralized and decentralized water infrastructures were considered for this assessment. Regional or local water resource availability, water treatment capacity, cost of the renewed infrastructure together with energy and climate change impacts were examined as strategies for this study.

In this dissertation, sustainability of centralized urban WDSs is investigated considering both current and future population and water demand scenarios. The possibility of using reclaimed wastewater for fire flow, indoor and outdoor non-potable water demand is considered in order to increase sustainability in an existing centralized water network.

2.3 Sustainability indicators and assessment methods

Since the definition of sustainable development, quantitative assessment of sustainability has become a major issue in literature. The mainly used method to assess sustainability is an indicator-based assessment methodology, which has been applied to many scientific fields from socio-economic science to environmental sciences. In addition, governmental institutions, researchers, or organizations have developed sustainability assessment frameworks. For example, OECD (1993) defined a sustainability assessment framework called Pressure-State-Response.

Indicators are defined as a group of information that summarizes the most crucial property complex and dynamic phenomena. These indicators are used to quantify and analyze the current trends and anticipate future conditions (Lundin 2003, Godfrey and Todd 2001). Indicators are specifically used to evaluate and monitor the multi-dimensional aspects of sustainability. Transforming qualitative sustainability objectives into indicators assists organizations and governmental institutions to evaluate the policies and progresses that are achieved towards sustainability (Milman and Short 2008).

Flint (2004) defined characteristics of indicators with respect to water supply sustainability. Sustainability indicators should connect economy, society and environment. It should be accepted by the communities and reflect the communities and stakeholders concerns. Sustainability indicators should also monitor, analyze and communicate local trends. The clear and scientifically defensible goals and issues should be addressed by the indicators. The uncertainties with respect to changing public perception or long-term interest should be integrated into the indicators. Local as well as regional or global goals should be considered and measured for a specific geography or an appropriate time scale. Once the sustainability indicators are identified for specific long-term problems, thresholds are set to distinguish sustainable and unsustainable practices.

Malmqvist et al. (2006) defined sustainability indicators for the strategic planning of wastewater management in Uppsala, Sweden. Sustainability indicators were defined

together with a group of researchers and employees from the municipality of Uppsala city through a decision-making workshop. They classified the indicators into 5 groups of criteria: health, environment, economy, socio-culture, and technical function. Environmental sustainability criteria of wastewater systems were defined using eutrophication, nutrient recycling, toxic compounds to soil, and energy use indicators. The risk of accidents was classified as the technical function indicator. Graymore et al. (2009) proposed a DSS incorporating sustainability indicators with a MCDA and geographic information system (GIS) in order to assess the regional sustainability in south west Victoria. In this study, not only the sustainability indicators relevant to the region, but also interactions and relationships between the indicators were considered. Sustainability indicators for the southwest Victoria sub-catchment area were grouped into three objectives; environmental, social and economic. In this region, agricultural, industrial and urbanization had severe impact on the environment. Therefore, relative environmental indicators were defined as land use, remnant vegetation, dryland salinity, wind erosion, water erosion and soil structure. Each indicator was given scores and the MCDA was applied for the overall sustainability assessment.

Mayer (2008) categorized SI assessments into two: "bottom up" approaches which are based on averages, principle components and information theory, and "top down" which is based on limiting the available resources and subtracting the consumption or degradation. One example for "bottom up" approach is an environmental SI proposed by Esty et al. (2006). In this methodology, 76 indicators were grouped and aggregated into 21 sub-indices, which were then grouped into 5 disciplinary components, and finally these components were aggregated into a single index. An example for "top down" approach is an ecological footprint index which was based on total energy consumption per hectares and required photosynthesizing to absorb the CO_2 emission in order to cancel the negative impact of energy consumption (Rees 2002).

Foxon et al. (2002) proposed a DSS for the UK water industry. Sustainability criteria and indicators for each criterion for water and wastewater systems were defined in four categories: economic, environmental, social and technical. The annual freshwater withdrawal, energy consumption sustainability indicators were considered under the resource utilization criterion. Service provision and environmental impacts are considered in the environmental category. In addition, performance of the water systems, reliability, durability, flexibility and adaptability were defined in the category of technical sustainability.

Mayer (2008) discussed the advantages and disadvantages of using sustainability indices which could be very powerful tools when developed through decision makers and used properly. Indices could guide societies towards sustainable conditions. Sustainability assessment using indices involves aggregation methodologies in order to achieve an overall index for the entire system. These aggregation methods are intuitive and will influence the final results. Mayer (2008)

states that none of the SI methods could overcome this problem. Decision makers, policy analysts should consider this problem while making decisions. Loucks and Galdwell (1999) proposed a SI methodology for water resources system using a weighted combination of reliability, resiliency and vulnerability indicators which can be applied to various economic, environmental, ecological and social criteria. The main feature of this methodology is that it is based on time-series values of the criteria so that the sustainability of water resources systems performance can be measured over time for the future. Loucks and Galdwell (1999) stated that the sustainable water systems should demonstrate properties of high reliability and resiliency and low vulnerability.

In this dissertation, sustainability of a WDS is assessed using environmental and technical sustainability indicators. The environmental sustainability indicators for a water infrastructure are identified as total fresh water use and energy intensity. The technical sustainability of a water network is evaluated using the SI methodology which is proposed by Loucks and Galdwell (1999). The details of this methodology are discussed in the following sections.

2.4   Sustainability Index

2.4.1   Reliability

Reliability is the probability that a single criterion is in the satisfactory state in a certain period of time (Loucks 1997). According to Loucks (1997) reliability could be measured by the following equation.

$$\text{Reliability of C} = \frac{\text{number of satisfactory } C_t \text{ values}}{\text{total number of simulated perids T}} \qquad (2.1)$$

where C is a selected criterion, C_t is the value for the selected criterion at time step t, and T is the simulation time period. It is important to acknowledge that the `satisfactory state` for a criterion is subjective and defined by decision makers` judgments or goals. It can also be defined considering the well-defined standards (Loucks 1997).

Ostfeld (2001) categorized the reliability of WDSs into two main groups: one is called "topological reliability" and the other one is "hydraulic reliability". Topological reliability is based on the physical connectivity of demand points. Each demand point must be physically connected to at least one resource. This method does not consider if the consumers get service during the failure but only the connectivity between nodes. The hydraulic reliability in the water networks is defined as the probability that water demand at each node is met over a certain period of time. This

also includes that the provided water should be at desired nodal pressures at the desired location and at the desired time.

Reliability analysis has been applied to WDSs including but not restricted to the definition that was proposed by Loucks (1997). For example, Tabesh et al. (2010) used hydraulic simulation tools together with GIS models to examine the reliability of WDS. The main aim of the study was to identify renovation schemas for water distribution networks with respect to proposed criteria (i.e. pipe break and leakage analysis, hydraulic and water quality performance as well as mechanical reliability of the network). Piratla and Ariaratnam (2012) modelled a sustainable WDS using multi objective genetic algorithm and EPANET. The model included tradeoffs between hydraulic reliability, life cycle cost and CO_2 emissions. Numbers of scenarios were developed in order to test and validate the model.

Christodoulou (2011) proposed a reliability analysis based methodology in order to effectively repair or replace the aging water mains. In this study, it is emphasize that for future sustainable urban water infrastructure should be based on the assessing the risk of failures and employing measures that would assist to prevent such failures. Tanyimboh and Setiadi (2008) proposed an optimization method for water distribution network using a multi-criteria maximum entropy approach and head-dependent modelling. The tradeoffs between capital costs, entropy, hydraulic reliability of the system and redundancy are studied. Although it was claimed that the proposed method was quick and effective in terms of locating pareto-optimal solution, it was acknowledged that the uncertainty of demand variations would affect the network entropy and hydraulic reliability which was not considered in this article.

2.4.2 Vulnerability

Vulnerability is a statistical measure of the extent or duration of failure (i.e. unsatisfactory value), should a failure occur (Loucks and Gladwell 1999). Loucks and van Beek (2005) defined vulnerability as the average failure. Mendoza et al. (1997) expressed vulnerability as the probability of exceeding a certain deficit threshold.

Sandoval-Solis (2011) used the following equation to calculate vulnerability.

$$\text{Vul}^i = \frac{\left(\sum_{t=0}^{t=n} D_t^i\right) / \text{Number of times } D_t^i > 0 \text{ occured}}{\text{Water demand}^i} \tag{2.2}$$

where Vul^i is te time-based vulnerability, $\sum_{t=0}^{t=n} D_t^i$ is the sum of water demand shortfalls for i-th water user. This equation basically states that the actual values of the unsatisfactory conditions are divided by the total number of unsatisfactory conditions occur. In order to make the vulnerability index dimensionless, it is

divided by the annual water demand (i.e. sum of all values). Loucks and Gladwell (1999) stated that there are number of ways to define the degree of failure of any criterion "C". For example, the "extent-vulnerability" defined as;

Individual extent-vulnerability (p) of C = Maximum extent of individual failure of criterion C occurring with probability p, or that may be exceeded with probability 1 – p.

Cumulative extent-vulnerability (p) of C = Maximum extent of cumulative failure of criterion C occurring with probability p, or that may be exceeded with probability 1 – p.

Loucks and Gladwell (1999) also defined the extent of vulnerability based on the expected of maximum observed individual of cumulative extent of failure.

Conditional expected extent of vulnerability of any criterion C =

$$\frac{\sum_t \text{individual (or continuous cumulative)extents of failure of } C_t}{\text{Number of individual (or continuous series of)failure events}} \quad (2.3)$$

Unconditional expected extent of vulnerability of any criterion C =

$$\frac{\sum_t \text{individual (or continuous cumulative)extents of failure of } C_t}{\text{Total number of simulation time periods,T}} \quad (2.4)$$

For some criteria, such as droughts, the duration of failure is as important as the individual of cumulative extents of failures (Loucks and Gladwell 1999).

Duration-Vulnerability (p) of criterion C = Maximum duration (number of time periods) of a continuous series of failure events for criterion C occurring with probability p or that may be exceed with probability 1-p

Expected Duration-Vulnerability of criterion C = Total number of time periods t having failures of C_t / Number of continuous series of failure events.

Dimensionless vulnerability (i.e. relative vulnerability) is calculated by following equation.

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$$\text{Relative vulnerability (C)} = \frac{\text{vulnerability(C)}}{\text{Max vulnerabilty(C)among alternatives}} \qquad (2.5)$$

Loucks (1997) stated that the relative vulnerability concept could be applied to any of type of vulnerability by using Max vulnerability (C) as a dominator.

Kay (2000) defined the vulnerability as the extent of duration of failures occurrence and measured by dividing cumulative extent of unsatisfactory values by the sum of all values in the analysis time period.

$$\text{Vul} = \frac{\sum \text{unsatisfactory}}{\sum \text{all values}} \qquad (2.6)$$

Similarly, Huizar et al. (2011) used the vulnerability index to create a DSS for long-term water supply planning in order to assess the effects of population growth and climate change on groundwater and surface water supply. In this study, the vulnerability is defined as the magnitude of failure and calculated as;

$$1 - \frac{\text{Demand not met}}{\text{User demand}} \qquad (2.7)$$

where "Demand not met" refers to the total amount of water demand (i.e. Gallons Per Capita Daily) that is not met divided by "user demand" which is the total demand for the year. In order to make the value of 1 satisfactory and 0 unsatisfactory, the fraction is subtracted from 1. Yilmaz and Harmancioglu (2010) proposed a multi-criteria decision-making framework in order to assess water resource management strategies with respect to several hydro-meteorological scenarios (i.e. baseline condition, worse-case scenario, an optimistic approach). In order to evaluate the environmental, social and economic sustainability objectives, reliability, resiliency and vulnerability performance measures were calculated. This study focused on expected-extent of vulnerability without considering the durations of failures. The vulnerability is measured as;

$$\text{VU of (C)} = \frac{\sum \text{individual extents of } C_t \text{ failures}}{\text{Total number of individual extents of } C_t \text{ failures}} \qquad (2.8)$$

where VU is the vulnerability, C_t is time series value for the selected criteria C, t is the simulation time period. Giacomoni and Zechman (2011) assess the SI using reliability, resiliency and vulnerability performance measures together with a Complex Adaptive Systems approach to evaluate the alternative land use and water management strategies. In this study, the SI is assessed using the relative extent of

vulnerability and relative duration of vulnerability which are calculated using the following functions.

$$\text{Extent Vulnerability} = \frac{\sum \text{Deviations of unsatisfactory conditions}}{\text{number of failures}} \qquad (2.9)$$

$$\text{Duration Vulnerability} = \frac{\text{number of failures}}{\text{Number of continuous failure events}} \qquad (2.10)$$

$$\text{Relative Extent Vulnerability} = \frac{\text{Extent vulnerability}}{\text{Maximum extent vulnerability}} \qquad (2.11)$$

$$\text{Relative Duration Vulnerability} = \frac{\text{Duration vulnerability}}{\text{Maximum duration vulnerability}} \qquad (2.12)$$

There are also scenario-based or indicator-based vulnerability assessments in the literature. For example, Li and Merchant (2013) proposed a modelling framework in order to assess the groundwater vulnerability using a GIS in North Dakota, USA. Several scenarios are proposed considering future climate and land use changes in the study area. Gober and Kirkwood (2010) investigated the vulnerability of water supply due to the climate change impact using a dynamic simulation tool called WaterSim in Phoenix, Arizona, USA. They proposed several demand-oriented climate scenarios and emphasized the uncertainty of water supply availability in the future which result in high vulnerability due to water shortage in the Phoenix area. Hamouda et al. (2009) proposed an indicator-based methodology in order to evaluate vulnerability if water supply systems in the Eastern Nile Basin.

2.4.3 Resiliency

Resiliency indicates how fast the system recovers from a failure which is mathematically defined by Loucks (1997) as following;

$$\text{Resiliency of a criterion C} = \frac{\text{number of times satisfactory } C_t \text{ follows unsatisfactory } C_t}{\text{number of unsatisfactory } C_t \text{ values}} \qquad (2.13)$$

Although Loucks (1997) defines resiliency for water supply management, interdisciplinary fields (i.e. sustainability science) has focused on sustainability together with the resiliency concept. The resiliency concept has a broad domain from engineering systems to the social perspective. For example, Rijke et al. (2013) established a social science research project that investigates the resilient urban water

resource management options (i.e. water sensitive city) in Australia. In this study, a water sensitive city is defined as resilient to the instantaneous or gradual changes. Their framework includes an adaptation process for the transition to water sensitive cities considering several compositions of centralized and decentralized systems as well as formal and informal governance strategies. These strategies are particularly helpful for policy makers in order to overcome the challenges of transforming to water sensitive cities in the future.

Ahern (2011) defined resilient systems as "safe to fail' and proposed strategies in order to increase the capacity of systems in the urban planning and design field. These strategies include multi-functionality, redundancy, bio diversity as well as social diversity, multi-scale networks and connectivity and adaptive planning and design. Cumming (2011) discussed a spatial resiliency concept in the context of landscape ecology and sustainability. Spatial resiliency is defined as the changes in the resiliency of a system when there is a spatial and temporal scale deviation. Duh et al. (2008) investigated the relationship between urbanization rate and water and air quality in the urban area with respect to identified resiliency factors. They suggested that the resiliency factors, once determined carefully, could be integrated into metrics, which would enable evaluation of resiliency of any human and natural systems over specific time and space.

In the water resources field, resiliency theory has been integrated into the future water management policies in order to assess the systems' flexibility since climate condition around the world is unstable and subject to uncertainty (Sandoval-Solis 2011). In fact, it has been more than decades that researchers have been working on resiliency analysis. For example, Todini (2000) proposed a resiliency index for designing looped water distribution networks. In this study, resiliency defined as a systems' capacity to overcome stress or failure. The main feature of this study was that to increase the resiliency which would eventually assist in increasing the reliability of the system under modified or stress conditions. Todini (2000) emphasized the tradeoff between the cost and resiliency and proposed to provide resilient looped network by increasing the energetic redundancy. In a more recent study, Banos et al. (2011) compared three different resiliency indices which were proposed previously by researchers (i.e. Todini 2000, Prasad and Park 2004, Jayaram and Srinivasan 2008) together with the water network investment costs in order to evaluate the performance of these indices. Banos et al. (2011) concluded that none of the resiliency indices considered the uncertainty of adequate supply-demand relationship but rather focused on adequate nodal pressures while designing a water distribution network.

2.4.4 Sustainability index

Reliability, resiliency and vulnerability performance criteria have been used in order to assess different aspects of water resources systems. Asefa et al. (2014) investigated

a complex water supply system using reliability, resiliency and vulnerability performance criteria. Water treatment production levels, reservoir capacities, surface water withdrawal permit levels considering future water demand have been integrated into sixteen distinctive scenarios. Although performance criteria (i.e. reliability, resiliency and vulnerability) have not been combined into a SI, they were used in a Monte-Carlo based framework in order to assess the outcomes of each scenario.

Mondal et al. (2010) used performance criteria for a risk-based evaluation of meeting future water demand in Bangladesh. Influence of climate change on future water demand in 2050 was investigated using a scenario-based approach. In this study, results of reliability, resiliency and vulnerability in each scenario have been evaluated separately rather than combining into a single index. Tradeoffs between these criteria are expressed by a decision makers' judgment. Kjeldsen and Rosbjerg (2004) investigated the relationships between the reliability, resiliency and vulnerability performance criteria for water resources system. They concluded that there was a strong correlation between resiliency and vulnerability which means the sustainable water resources systems tend to have a low vulnerability index while they have high degree of resiliency.

In another study, a multi-criteria framework was proposed for designing and managing reservoir operations. Monte-Carlo simulation was used to create the long and short term memory models for reservoir and reliability, resiliency and vulnerability. Performance indices were observed for municipal and industrial water supply and for irrigation demand. Authors of this study claimed that the performance indices together with the MCDA were a useful tool to interpret the tradeoffs and consequences of reservoir management policies (Jain and Bhunya 2008). Hoque et al. (2010) used reliability, resiliency and vulnerability performance criteria in order to assess the health of the Cedar Creek watershed in North East Indiana, USA. Stream water quality data was reconstructed and a Bayesian algorithm was used to quantify the errors. They found that the proposed methodology was effective in terms of evaluating impacts of stressors in a watershed. In addition, authors emphasized the practicality of using reliability, resiliency and vulnerability to assess the health of a watershed.

Loucks (1997) first presented a SI methodology which was a weighted combination of reliability, resiliency and vulnerability performance criteria. Calculation of SI could be performed in two steps. First, the vulnerability indicator of each criterion should be a similar measure to resiliency and reliability indices (i.e. dimensionless). This step is achieved by calculating "relative vulnerability". The second step involves converting minimum and maximum values for relative vulnerability. Namely, relative vulnerability should be ranging from "0" is undesirable condition, "1"is preferable condition. For that reason, the outcome of "relative vulnerability" was subtracted from "0". Following these steps, the SI could be calculated using the following equation.

$$\text{Sustainability(C)} =$$
$$[\text{Reliability(C)}] * [\text{Resiliency(C)}] * [\textstyle\prod_v\{1 - \text{relative vulnerability\_v(C)}\} \qquad (2.14)$$

where relative vulnerability_v (C) is the v-th type of calculated relative vulnerability. One property of this SI is that if one of the performance indicators is "0", the result of the SI is "0". In addition, the SI will only have a high value if all of the performance indices have high values.

If there is more than one criterion in the decision process, sustainability indices of each criterion can be combined into a single value by assigning weights based on the relative importance of the each criterion. Loucks (1997) calls this "relative sustainability" as given in following equation.

$$\text{Relative sustainability} = \textstyle\sum_C W_c \text{ Sustainability(C)} \qquad (2.15)$$

where W_C is the relative weight of the corresponding criterion, and the sum of the weights must be equal to 1. Since Loucks (1997) proposed the SI methodology, it has been applied to solve the water resources sustainability issues around the world. Sandoval-Solis et al. (2011) has modified and extent the SI calculation in order to assess the sustainability of water management policies in the Rio Grande, Mexico. They used the following sustainability equation to calculate the SI.

$$SI^i = Rel^i * Res^i * (1 - Vul^i) \qquad (2.16)$$

where SI^i is the sustainability index for i-th water user. In order to compare the groups of water users, they used a method similar to "relative sustainability" calculation but it is called "Sustainability by Group". The difference is that they have proposed using the water demand of i-th water user as a weighting factor, which is normalized by dividing i-th water users' demand by the annual water demand.

Giacomoni and Zechman (2011) assessed the sustainability of urban water resources using a complex adaptive system methodology together with the SI approach. In this study, the SI provided a comparison tool for several water management scenarios and adaptive strategies. In this study, the SI was defined as;

$$\text{Sustainability Index} = \text{Reliability} * \text{Resiliency} * (1 - \text{Relative Extent Vulnerability}) *$$
$$(1 - \text{Relative Duration Vulnerability})$$
$$(2.17)$$

The way they calculated the relative extent vulnerability and relative duration vulnerability were given in the vulnerability section. The scenarios are built using a complex adaptive system approach. The SI was used to compare the outcomes of these scenarios. They concluded that the adaptive strategies would assist to increase reliability and resiliency of urban water supply systems.

Huizar et al. (2011) proposed a DSS model by quantifying scenario-based future water supply and demand policies using the SI methodology. Their aim in this study was to assist decision makers and stakeholders by demonstrating the future water conditions. This scenario-based sustainability assessment was applied to a regional water supply system in Tuscon, Arizona. In this study, sustainability was defined as the long-term system ability of achieving a satisfactory state and calculated for a single user, for all users, and for the supply using the following equations respectively.

$$1 - \frac{\sum_t \text{Demand not met}}{\sum_t \text{Users Demand}} \tag{2.18}$$

$$1 - \frac{\sum_t \text{Total demand not met}}{\sum_t \text{Total demand}} \tag{2.19}$$

$$1 - \frac{\sum |\text{Deficit}|}{\sum \text{Recharge}} \tag{2.20}$$

where "Demand not met" refers to the total amount of water demand (i.e. Gallons Per Capita Daily) that is not met divided by "user demand" which is the total demand for the year, $\sum |\text{Deficit}|$ is the amount of water that is withdrawn from the aquifer, $\sum \text{Recharge}$ is the total amount of water recharged. As can be seen in this study, sustainability was not defined as a weighted combination of reliability, resiliency and vulnerability. However, results of each scenario were compared using all of the performance criteria (i.e. reliability, resiliency and vulnerability) as well as the previously defined sustainability.

Yilmaz and Harmancioglu (2010) proposed an indicator-based evaluation of water management alternatives in the Gediz River Basin, Turkey. Overall 9 economic, environmental and social sustainability indicators are proposed and three different multi-criteria decision analyses were applied to combine these indicators. Three different hydro-meteorological scenarios were proposed to assess several water supply and demand variations. The environmental sustainability indicators were agricultural SI, environmental SI, and water exploitation rate. These sustainability indices were calculated using reliability, resiliency and vulnerability performance criteria which were defined as;

$$\text{ASI} = \text{RE}_{(S_i/D_i)} * \text{RS}_{(S_i/D_i)} * (1 - \text{VU}_{(S_i/D_i)}) \tag{2.21}$$

$$\text{ESI} = \text{RE}_{(S_e/D_e)} * \text{RS}_{(S_e/D_e)} * (1 - \text{VU}_{(S_e/D_e)}) \tag{2.22}$$

where ASI is the agricultural SI, ESI is the environmental SI, S/D is the supply and demand ratio at the district. Although three different MCDA tools (i.e. simple additive weighting, compromise programming, and technique for order preference by similarity to ideal solution (TOPSIS)) were used in this study, the authors concluded that the results were independent of the multi-criteria method that was used but sensitive to the assigned weights.

2.5 Water distribution systems

Construction, operation and maintenance of water infrastructure and providing water services to communities are the responsibilities of water utilities. There are six functional components of water utilities; source development, raw water transmission, raw water storage, treatment, finished water storage, and finished water distribution. There are basic functions to obtain freshwater from a source and deliver to a water treatment facility and then to the customers. While finished water storage and distribution are assessed together, raw water storage and source development are evaluated collectively (Mays 2000).

There are three main components of urban water distribution; distribution piping, distribution storage and pumping stations. Distribution piping can be designed as loop or branched or both and is composed of pipes (i.e. links) which are the most abundant component of a water network. The end of pipes or interception of several pipes are called nodes and could be either junction nodes or fixed-grade nodes. Junction nodes have demands that vary over time while fixed grade nodes are attached to a reservoir, tanks or large constant pressure mains (Mays 2000).

Valves in the WDSs are used to regulate the flow or pressure. Storage tanks are used to provide water for fire flow or to meet high system demands (Mays 2000). Pumps have an important role of providing or maintaining energy in order to transfer water from reservoir to treatment facility or to demand points with sufficient pressure (Tanyimboh and Key 2011).

2.5.1 Water distribution systems modeling

Planning, designing, operation and maintenance of WDSs have become more and more important as cities are growing and demanding more infrastructure components to provide service. The WDS modeling (i.e. computer modeling) is used to observe the behavior of water networks which could be steady-state models,

dynamic or water quality models. There are a number of commercial (i.e. WaterGEMS, H2ONET, InfoWorks etc.) and open software (i.e. EPANET) that enable computer simulations to model water networks (Savic et al. 2011).

2.5.1.1 *Steady state analysis*

In order to understand the initial state of the system effectively, it is necessary to conduct steady state analysis before proceeding further with the complex simulations. Essentially, steady state analysis is a single time period analysis that is practiced to compute the nodal pressures, flow rates, velocities etc. in the pipes (Rossman 2000). This simulation provides a snapshot of hydraulic conditions in water networks assuming all the nodes have constant water demand. It is mostly used for infrastructure design for example pipe sizing considering a peak demand condition (Savic et al. 2011).

2.5.1.2 *Extended period simulation*

The extended period simulation (EPS) brings a time dimension into hydraulic modelling. In other words, the EPS enables users to simulate demand variability over time and understand how hydraulics and water quality change periodically. The EPS is specifically useful to observe the behaviour of WDSs under fluctuating demands or in emergency situations (i.e. a fire event). Savic et al. (2011) states that the EPS model could be effective and robust tool to enhance the efficiency of water infrastructure and to provide sustainable water services over a long period of time.

In order to conduct an EPS simulation not only constant variables (i.e. pipe diameters, roughness, elevation etc.) but also time-varying data (i.e. demand pattern to represent water demand fluctuation during the day, pump operation or reservoir levels) are required. The duration of the EPS depends on the type and purpose of the analysis that is conducted. Savic et al. (2011) also state that the reservoir storage analysis should be simulated for at least 24 hours while the water quality analysis simulations requires longer period of time in order to see the changes in quality. The EPANET enables EPSs in the WDS in order to model hydraulic efficiency and water quality changes over time. The water quality models are specifically useful to model chlorine decay, source water mixing, contamination spread and water age (Savic et al. 2011).

Water age models in WDSs provide general understanding about chlorine decay and bacterial growth issues. The higher the water age, the more susceptible is the water networks to these issues. Water quality models are complex and require period sampling throughout the network in order to successfully predict chlorine and other chemical reactions. Some computer models (i.e. EPANET) enable possible water quality issues based on velocity and flow changes in the network (Savic et al. 2011).

Digiano et al. (2009) modelled water quality for an existing water network in Chatham County North Carolina. They proposed a non-potable WDS to meet the fire flow and non-potable water demand such as toilet flushing and outdoor irrigation. The results showed that omitting the fire flow from the potable water network could assist reducing water ages by approximately 75%. This was due to the fact that the pipe diameters in the potable water network have been reduced in size since the fire flow would be met using the non-potable WDS.

Savic et al. (2011) stated that the hydraulic efficiency models could also be used to identify sediment-based water quality issues. Generally, the pipes with peak velocities less than 0.3-0.4 m/s contains the risk of sediment build-up, whereas the pipes with peak velocities higher than 0.6-0.8 m/s have less risk since the velocities are high enough to provide self-cleaning for pipes.

The EPS within the EPANET software is used to model hydraulic efficiency of the water networks. For example, Georgescu et al. (2014) used the EPANET software in order to conduct an EPS model. This model was used to apply variable speed functioning algorithm for pumps using rule-based controls in the EPANET software. The daily variation of the flow rates were simulated with a demand pattern over a 24-hour period of time. Tabesh et al. (2010) proposed an index-based methodology for rehabilitation and renovation of WDSs. The EPSs were applied together with the proposed indices to determine rehabilitation strategies, which were based on the reliability of the system, hydraulic efficiency and water quality measures as well as pipe break and leakage analysis. The EPANET software was integrated into the GIS (i.e. ArcView) in order to increase the robustness and effectiveness of the methodology. The results showed that using a combination of proposed indices to create pipe replacement schemes might assist in developing more cost-effective strategies. In addition, this methodology may assist to improve hydraulic efficiency and water quality performance of the network.

Jun and Guoping (2013) proposed an extension for the EPANET software called EPANET-MNO in order to simulate more realistically the hydraulic performance of the network over time. Several combinations of nodal outflows were analyzed including volume-driven demand, pressure-dependent demand and leakage. The hydraulic performance of these pressure dependent demand functions were compared with respect to required pressure and minimum service pressure. The EPS is mostly used together with optimization models in order to design or modify the operation of WDSs, which will be discussed in the following section.

The EPS in this dissertation is used to assess the technical sustainability of the WDS. Specifically, hydraulic efficiency, water quality and energy intensity parameters are simulated over time using the EPS feature of the EPANET software.

The main objective for designing a WDS regardless of the complexity or simplicity of the water network is to provide secure supply at the lowest cost. For this purpose, the lower cost and higher reliability models are considered while designing the water network. In order to meet the hydraulic requirements (i.e. pressure, velocity, minimum operation cost etc.) and the engineering necessities (i.e. materials, system component configuration such as pump operation etc.) optimization models have been applied to the planning and design of WDSs (Vairavamoorthy et al. 2011).

Lansey (2000) stated that the costs of capital investment (i.e. pipes, pumps, tanks, valves), operation and maintenance (i.e. energy consumption) are the primary objective while designing the water networks. In addition, water demands should be met with adequate nodal pressure. Basic optimization objectives and constraints could be stated as;

> Minimize investment and energy costs
>
> Subject to:
>
>> Meeting hydraulic constraints
>>
>> Satisfying water demand
>>
>> Satisfy nodal pressure requirements (Lansey 2000).

A linear programming approach can be applied to branched WDSs using a split-pipe formulation which is based on splitting the pipes into different segments and optimizing the length and diameter of each section. Looped water distribution networks can be optimized via linearization. Non-linear programming can be applied to general system design which is based on integrating hydraulic simulations into the optimization method. This method is specifically useful to optimize the multiple demand conditions and operational problems. There are also stochastic search techniques such as evolutionary optimization, genetic algorithms, simulated annealing which are used to optimize the pipe sizes in the WDSs (Lansey 2000).

Optimization models are not only applied to water distribution design problems. For example, Goldman and Mays (2005) developed a methodology that linked a simulation annealing optimization technique with the EPANET to find optimal pump operation for a WDS while meeting both water quality and hydraulic performance requirements. Kurek and Ostfeld (2013) linked the EPANET with multi objective methodology using Strength Pareto Evolutionary Algorithm in order to demonstrate the tradeoffs between pumping cost, water quality and tank sizing of a WDS. Lim et al. (2008) analyzed two separate WDSs in order to preserve freshwater resources and decrease economic costs using the linear programming and non-linear programming methods. Optimization models are specifically used to minimize total freshwater flow rate which represents the environmental benefit and to minimize the operation costs which is considered as economic cost. The GAMS/MINOS solver was used to obtain the results for optimization. In addition to optimization methods, life

cycle assessment and life cycle cost analyses were used to compare water networks in terms of environmental and economic performances.

2.6   Scenario analysis

Scenario planning is defined as a tool to improve the decision-making process and to deal with uncertainty due to the application of different strategies (Varum and Melo 2007). Scenarios are not meant to predict or accurately explain the future but assist decision makers and stakeholders by reflecting the uncertainties or assumptions that are likely to happen in the future (Varum and Melo 2010). De Vries and Petersen (2009) stated that the scenarios should have a logical and consistent storyline which reflects certain worldviews of societies and regions that were under consideration. Each stakeholder can define a worldview from their own perspective. For example, the worldview of a military commander and a politician might not coincide. The purpose of scenario planning is to construct a model representing a collective worldview which is quantified using important system variables.

Scenario planning has been applied to many disciplines including the business world, water resources, urban and regional planning. Tapinos (2013) used a scenario planning approach on a cosmetic business unit in the UK. The case study showed that the scenario planning process assists stakeholders in understanding the future uncertainties in their business units as well as improving their skills of developing strategies to deal with those uncertainties. Weng et al. (2010) integrated a scenario planning approach with the MCDA in order to assess the impacts of water resources management policies in the Haihe River Basin, China. Scenario analysis was mainly used to evaluate the uncertainties due to a large scaled water resources management problem involving a number of parameters and the MCDA was used to evaluate the outcomes of the proposed scenarios. The result of this study showed that each water management policy option had a different impact on the regional economic development in China. Karolien et al. (2012) developed a set of scenarios in order to solve a rapid urban growth problem in Kampala, Uganda. It was stated that the rapid urban growth was affecting the quality of life and eventually not meeting the sustainable urban planning perspective. A baseline scenario as well as restrictive and stimulative scenarios was developed in order to reflect the urban growth patterns in 2030. They concluded that the business as usual (i.e. baseline) condition was "unsustainable" and further research was necessary to include visioning scenarios.

Different concepts and procedures of the scenario planning application have been explained by researchers over decades. For example Stewart et al. (2013) gave a detailed description and explanation for different perspectives of scenarios. They categorized the scenarios into four main groups: "Shell scenario and planning approach", "Scenarios for exploring uncertainty", "Scenarios for advocacy or political argument", "Representative sample of future states". The shell scenario planning approach was first explained by Van der Heijden (1996) consisting of a

storyline for the future to assess advantages and disadvantages for each of the policies and strategies. The highlight of this approach was the external uncertainties rather than the policy components in this approach. The scenario for exploring uncertainty was similar to the previous approach but the difference is that there are no identified strategies to evaluate. This approach focuses on the outcomes of several combinations of uncertainties and how these could shape or alter the future. Scenarios for advocacy or political argument were a set of parameters that are either against or in favor of certain political action. Finally, representative sample of future states was a rather technical approach using a multivariate probability distribution in order to represent the outcomes of a small number of alternatives in the sample space (Stewart et al. 2013).

In another study, Börjeson et al. (2006) categorized scenario techniques based on a problem that was expected to be solved in the future. Each type of scenario answers a specific question as given in Table 2.1. They proposed three main scenario types; predictive, explorative and normative which answers the questions "What will happen", "What can happen?", and "How can a specific goal be achieved?", respectively. These scenario types are further divided into sub-categories as given in Table 1. In this study, it was emphasized that the scenarios should be useful and maintain specific targets for decision makers and stakeholders. For this purpose, they created a guideline to explain a typology of scenario studies.

There are a large number of methodologies in the literature to build and evaluate scenarios. Some of these scenarios are based on simplicity while some of them have complex structures. There are also qualitative approaches, or statistical and computational methods to accomplish scenario based evaluation (Vecchiato and Roveda 2010). For example, one approach proposes categorizing future states and conditions into six foundational concepts: the used future, the disowned future, alternative futures, alignment, models of social change, and uses of the future. This study was proposed to apply scenario analysis in social science and economic changes (Inayatullah 2008). Another approach proposed by List (2007), which was based on a wide range of stakeholder participation to create "Scenario Network Mapping", was very flexible and target-specific. In addition, there are a wide range of review articles in the literature which focus on the scenario planning applications and techniques such as Amer et al. (2013), Stewart et al. (2013), Bishop et al. (2007).

In these water resources management models, the scenario planning approach has been used to support the decision-making processes. Black et al. (2014) provided a guidance to apply scenario analysis in the water resources field. Sandoval-Solis (2013) proposed a scenario-based water management policy evaluation in a severely water stressed river basin in Rio Grande. The scenarios were built using inputs from stakeholders as well as international regulatory obligations and environmental objectives. Ni et al. (2012) proposed a set of scenarios assuming that the water supply and demand ratio could become a serious issue by 2020 in China. Scenarios were considering economic development and environmental protection objectives in order

to achieve an optimal combination of the two for future development plans. Woods et al. (2012) used the scenario planning approach for designing a robust water supply infrastructure. Scenarios that were proposed in this study were based on the integration of potable and non-potable (i.e. reclaimed/recycled water) water use in southern Pima County and southeastern Tuscon, Arizona, USA.

Table 2.1 Scenario types and features (Adapted from Börjeson et al. 2006)

1. Predictive "What will happen?"		
	1.1. Forecast	**1.2. What-If**
Main question	"What will happen on the condition that the likely developments occur?"	"What will happen on the condition that some specified events occur?"
Main features	Resulting scenario is likely to happen	Probabilistic scenario based on historical data
	Often short-term	Often short-term
Example	Economic events, natural phenomena	World energy outlook 2002
2. Explorative "What can happen?"		
	2.1. External	**2.2. Strategic**
Main question	"What can happen to the development of external factors?"	"What can happen if we act in a certain way?"
Main features	Policies are not part of this scenario type.	Consequences of specific policies of strategies are investigated
	Outcomes of the scenarios can be used to create policies	Often long-term
	Often long-term	
Example	Global energy or climate change scenarios	
3. Normative "How can a specific goal be achieved?"		
	3.1. Preserving	**3.2. Transforming**
Main question	"How can a specific goal be achieved by adjusting current situation?"	How can a specific goal can be achieved when the prevailing structure block necessary changes?"
Main features	Often long-term	Often very long-term
	Optimization models	Finding an option that satisfies long-term targets (i.e. Requires marginal adjustments)
Example	Regional planning based on expert judgments to reach a specific goal	Societal problems

2.7 Visualization and decision support systems

2.7.1 Spatial decision support systems and multi-criteria decision analysis

The DSS is a concept that emerged in the early 1970s as a part of decision theory and used to solve semi-structured, unstructured or even "wicked" problems (Gorry and Morton 1971, Shim et al. 2002, Courtney 2001). Shim et al. (2002) defined DSSs as a computer-aid solution for the complex problems to support the decision-making process. Spatial DSSs have evolved together with the emergent DSS concept in order to assist decision makers or stakeholders to increase the effectiveness of the decision-making processes by solving semi structural spatial decision problems (Malczewski 1999). There are six generic characteristics of DSSs which also apply for spatial DSSs (Malczewski 1999):

1. It should be designed to solve ill-structured problems

2. It should have an uncomplicated interface for users

3. It should integrate analytical models with data

4. It should be able to explore solution space by building alternatives

5. It should support a variety of decision-making styles

6. It should allow interactive and recursive problem solving

In addition to these six properties, spatial DSSs have four distinguished features (Densham 1991):

1. Input of geographic data

2. Representation of the spatial relationships and structures

3. Application of spatial analysis

4. Produce geographic outputs (i.e. maps)

There are increasing numbers of examples using DSS and spatial-DSS in the water resources management field focusing on solving current and future water resources sustainability problems. Giupponi (2007) proposed a DSS for water management problems by implementing the strategies given in the European Union Water Framework. The project called MULINO (i.e. Multi-sectoral Integrated and Operational DSS for sustainable use of water resources at catchment scale) focused on socio-economic and environmental aspects of river basin management and aimed to improve the quality of the decision-making process by integrating the GIS and multi-criteria decision methods. In a similar study, the sustainability of Glenelg Hopkins catchment management area in Victoria, Australia was evaluated by creating a GIS-based DSS using multi-criteria analysis techniques (Graymore et al.

2009). In this study, a set of environmental and socio-economic sustainability indicators were identified and sustainability scores were calculated for each sub-catchment area by aggregating the indicators using weighted summation. Zeng et al. (2012) developed a DSS to assess the water management problems in Daegu City, Korea using an artificial neural network and generic algorithms. The proposed DSS was web-based and contains hydrological and urban water demand forecasting models as well as a water management model. This web-based DSS assisted decision makers in conducting spatial queries, scenario analysis and generic algorithms for the water resources allocation. In another study, Weng et al. (2010) integrated scenario analysis and a multi-criteria DSS for water resources management purposes in the Haihe River Basin, China. It was emphasized that scenario-based DSSs could be a robust tool to evaluate long term complex and conflicting objectives involving water resources management policies. Scenario analysis was specifically used to deal with the uncertainties while the MCDA was used to accomplish scenario evaluation.

Perhaps one of the more highly used decision analysis technique to create a DSS in the water resources management field is the MCDA, which is specifically integrated into GIS technologies to create spatial DSSs. The MCDA is a method to evaluate decision alternatives based on assigning weights to identified criteria and ranking each decision alternative in terms of its overall score (Hajkowicz 2007). Hajkowicz (2007) stated that the purpose of the MCDA was to provide options for decision makers rather than obtaining an absolute solution for a decision problem. The result of the multi-criteria analysis should present options to decision makers who could speculate about the possible outcomes of each action before they reach a consensus.

Moglia et al. (2012) used Subjective Logic in a basic Bayesian Network to accomplish a MCDA to assess integrated urban water management approaches. The purpose of this study was to create a logical and robust tool to evaluate different urban water system scenarios and to select the best outcome between alternative water management strategies. Results of their analysis showed that the traditional urban water systems had high reliability and low capital cost while alternative decentralized approaches did not satisfy these criteria. The novelty of this study was described as adding a reliability assessment for scenarios and adding judgments for the uncertainty embedded in each criterion. The MCDA was used in Switzerland together with scenario analysis in order to assess the WDS rehabilitation alternatives (Scholten et al. 2014). The aim of this study was to deliver a robust DSS for water utilities involving long-term water infrastructure rehabilitation strategies. There were three fundamental objectives in this study: minimize the cost, maximize the reliability of the water infrastructure and provide high intergenerational equity. These objectives were evaluated using a multi-attribute value model (Scholten et al. 2014).

2.7.2 Visualization and spatial decision support systems

Scenario analysis together with the MCDA has been used to evaluate decision alternatives as explained in the previous sections. One important property of scenarios is that they contain a large number of attributes or decision alternatives. As a result, it is more challenging to communicate with the complex data sets. Geographic visualization as a component of information visualization is a way to represent the complex scientific spatial data. Geographic visualization is used together with the analytical processes (i.e. multi-criteria analysis) to explore and analyze spatial and temporal data in order to assist decision makers and/or analysts to interpret the underlying problems (Rinner 2007). Computer-generated visualization techniques provide robust and effective tools by visualizing complex systems and combining scientific information with decision makers' perception (Rehr et al. 2014, Sheppard 2005, Tufte 1990, Fiore et al. 2009). Visualization tools and spatial DSSs might improve the effectiveness of the whole decision process by incorporating knowledge into the data and eventually would assist in providing sustainable water services.

Falcao et al. (2006) presented a spatial DSS for forest resources management planning in southwest Portugal. The visualization modules were used to address the geographic complexity of the forest landscape. The results showed that the proposed visualization tool is robust in terms of its navigation capabilities and assisting in evaluation of forest management scenarios. Castelletti et al. (2010) proposed a decision support model in order to solve environmental problems which contain large and dynamic models and multiple objectives. The conflicting objectives in this study were solved using the multi-objective optimization technique while the interactive visualization technique was used to improve the decision-making process. The methodology was applied to a water reservoir in New South Wales, Australia in order to resolve a water quality problem by relocating or adding new mixers which was used in the artificial de-stratification.

A successful visualization of the water network can assist decision makers in identifying problematic regions and to provide alternative solutions for sustainable water resources. Formetta et al. (2014) emphasized the importance of visualization and data processing tools to understand the outcomes of the hydrological models in the water resources field. Lee et al. (2010) visualized spatiotemporal water quality data of the Nakdong River, Korea in order to identify long-term improvements or deteriorations of water quality in the river system. They realized that the trend analysis readability in the raw data needed to be improved. Therefore, they proposed using graphs to perceive spatiotemporal trends in the data that were transformed by the LOWESS method. Best and Lewis (2010) visualized groundwater data in order to provide an educational tool for public or decision makers who were focusing on groundwater issues. Instead of using traditional techniques of reading numeric results on reports, the authors wanted to provide a robust tool to compare the results of simulation, different scenarios and time-varying data which would assist in the

decision-making process. Assaf and Saadeh (2008) designed a DSS in order to assist decision makers and stakeholders for the water quality management plans in the Upper Litani Basin, Lebanon. The Weap model was integrated into the GIS software in order to visualize the results of alternative water quality management scenarios.

In the 1980s and early 1990s, creating spatial DSSs were highly depending on the GIS software and the significant expertise were required in order to be able to modify or create a user specific interface. Recently, easier software development environments have been leading towards customization of graphical user interfaces. These user-friendly and problem specific interfaces enable a wider use of spatial DSSs since these customized interfaces do not require expertise to operate. For successful spatial DSS applications, user interfaces should be developed interactively together with stakeholders, experts and end-users (Sugumaran and Degroote 2011). Van Delden (2009) developed two separate user interfaces for a SDSS problem of regional planning in New Zealand. One interface was to simulate and visualize scenarios and to compare results for policy analysts. The other one was for modelers to update the data and change model parameters. Emberger et al. (2006) created a DSS tool called MARS model for simulating the travel behaviour of the population. The MARS was an interactive model with a unique graphical user interface. It is easier to use and straightforward such that decision makers simulate their own policy decision without any need for analyst or model expert.

Robust and efficient software interface designs would assist decision makers and stakeholders to be able to utilize the modelling components in the spatial DSS (Sugumaran and Degroote, 2011). In fact, user-friendly interfaces are so important that, unintuitive interfaces might even lead to failure of DSS (Evers 2007). Compas and Sugumaran (2004) developed a web-based spatial DSS using an Analytical Hierarchical Process that failed due to the complexity of the modelling approach. Users could not understand how the modelling components worked.

In this dissertation, a decision support tool is developed in order to assess results of a scenario evaluation and visualization through maps, graphs, tables and reports. Since decision makers' preferences have been considered for the first stage and integrated in the SI methodology, a decision support tool does not have to take input data via interaction, rather visualize the results, and then if requested, provide details for each scenario by operating queries.

CHAPTER 3

MATERIALS AND DATA TYPES

3.1 Introduction

This section is composed of detailed information about the study area and software packages that are used in this dissertation. The WDS that is used in this study is located in Arizona, USA. Note that the owner of the data does not want to give out the exact location of the water distribution network; therefore, the main location of the study is not provided in this dissertation. This chapter contains information about the population, flow rates, geo-morphologic features of the study area, as well as the information about data processing techniques that are being utilized in this dissertation.

3.2 Software packages

In this dissertation, a number of software packages are used in order to evaluate the sustainability of WDSs. The software packages that are listed below are mainly utilized to visualize, analyze, and simulate hydraulic efficiency and water quality in the urban WDSs.

3.2.1 EPANET software

The U.S. Environmental Protection Agency EPANET software is the commonly used open source software for hydraulic and water quality simulations (Rossman 2000). The EPANET software performs the EPS within pressurized water distribution networks in order to observe the hydraulic efficiency and water quality behaviors. A WDS is composed of pipes, nodes (i.e. junctions), pumps, and valves as well as a water resource which could be storage tanks and reservoirs or wells. The EPANET

software is able to track the water flow at each pipe, calculate nodal pressures, water ages or the concentration of chemical species at the entire WDS for the identified simulation period which may consist of multiple time steps.

The main purpose of the EPANET software is to support the understanding of how drinking water elements travel throughout the water network. It can be a part of a DSS to assess alternative water management strategies in order to improve water quality by;

- Enabling to use multiple source systems as well as the scheduled source utilization
- Modifying the pumping schedules and tank inflow or outflow
- Use of satellite treatment
- Targeted pipe cleaning and replacement

The other features of the EPANET software include editing network input data, running hydraulic and water quality analysis, and displaying the results of the analysis in thematic network maps, data tables and graphs and contour plots (Rossman 2000). Although, it is a very powerful tool to conduct hydraulic efficiency and water quality analysis, the one drawback with the EPANET software is that its visualization capabilities are very limited.

3.2.2 ArcGIS

The ArcGIS software is versatile and widely used GIS software which is created by ESRI, Redlands, California (ArcGIS Resources 2014). Generally, a GIS allows users to organize, manage, analyze and communicate with the geospatial data by visualizing and displaying relationships, patterns and trends. A large amount of maps and reports can be produced using the ArcGIS software not only to display information but also to interact with the data by queries and performing analysis. Maps are not only an end product of the GIS but also can be used as a tool to solve scientific problems (ESRI 2014). The main reason of using the ArcGIS software in this study is to utilize its visualization capabilities which are more effective than the EPANET software. In addition, data management properties of the ArcGIS software allow us to incorporate the EPANET software results (i.e. simulation reports) into the geospatial database. The ArcGIS software is composed of several applications including ArcMap, ArcCatalog, ArcToolbox, ArcGlobe and ArcScene. In this study, the ArcCatalog and ArcToolbox are used for the data management purposes and geo-processing, respectively while the ArcMap is used to display thematic maps and for queries etc. In addition, the ArcScene property is used for the 3D visualization of the elevation data.

3.2.3   GAMS

The General Algebraic Modeling System (GAMS) software stands for the "general algebraic modeling system" is a mathematical programming and optimization tool for modeling a large scale and complex applications. This is a high-level modeling system for the mathematical programming and optimization, consisting of a language compiler and a number of integrated high-performance solvers.   The GAMS software offers compact/portable modeling as well as a robust way to model linear, non-linear and mixed integer optimization problems. In addition, it is simple to modify/revise large models and convert from one solver to another. The linear programming is applied in this study to determine the minimum cost pipe sizes and pumping heads of the dual water networks.   The GAMS software is used as the solver for the optimization model developed herein (GAMS 2014).

3.2.4   Microsoft excel

The Microsoft excel offers the basic spreadsheet operations as well as data manipulations. In this dissertation, the EPANET software simulation results are exported into the excel software spreadsheets for further analysis. Specifically, the SI calculations of WDSs are conducted in the excel software using visual basic for applications (VBA) to implement numerical methods more efficiently.

3.3   Study area

The water network is composed of 181 junctions, two reservoirs, three storage tanks, 190 pipe sections, two pumps, and two check valves (i.e. butterfly valves). The input file for the EPANET modeling is given in Appendix 1. The majority of the pipe diameters are 6-inch ($\cong$ 150 mm) while they range from 2-inch ($\cong$ 60 mm) to 12-inch ($\cong$ 300 mm). Two reservoirs are located at the north side of the WDS. The pumps which are located at the same location are being used in order to pump water from the reservoirs into the water network. An outline of the entire WDS covering the locations of wells, pumps and storage tanks together with base demands of the nodes and diameters of the pipes are given in Figure 3.1.

It can be seen from Figure 3.1.A that base demands at the majority of nodes are less than 4 gallons per minute (GPM) while it can go up to 30 GPM. Although both reservoirs provide flow into the WDS, tracing analysis in the EPANET shows that the main water flow is supplied by the reservoir 1. Approximately 54 % of all pipes at the entire network are 6-inch and approximately 34% of these pipes are 8-inch. As can be seen in figure 3.1.B 6 and 8-inch pipes are small-sectioned pipes while the longer pipes are 10-inch.

According to the data provider, there are approximately 610 households and 29 commercial facilities in the study area. It is assumed that at each household there are

4 or 5 family members and the daily water consumption per person is approximately 180 gallons per day (GPD). Total base demand of the study area is approximately 385 GPM ($\cong$87 m³/h) while total storage tank inflows are circa 445 GPM (101 m³/h). Elevation is not available continuously for the entire study area, however, elevations at the nodes of water distribution network is used to create a complete surface.
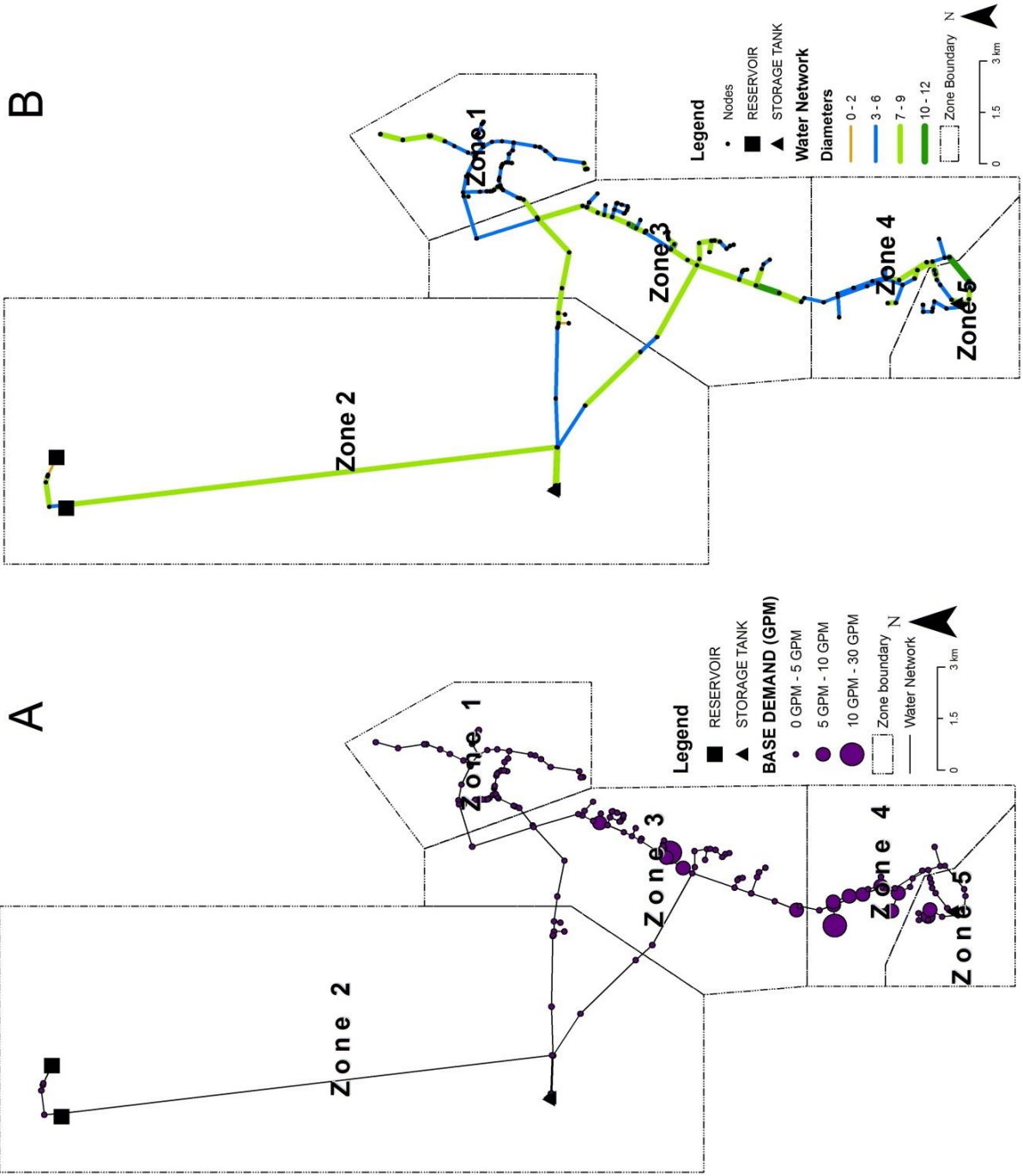
Figure 3.1 A. Base demands of the study area B. pipe diameters of the study area.

Figure 3.2 represents the complete surface elevation of the study area. The relative elevation at the study area ranges between a minimum of 320 ft (equivalent of 96-m) to a maximum of 622 ft (equivalent of 190-m). Figure 3.2.A is created by contour mapping embedded in the EPANET software while figure 3.2.B is created in a GIS environment. The elevation data set of the nodes in the study area is exported into the ArcGIS and the inverse distance-weighting algorithm is used to create a continuous surface.
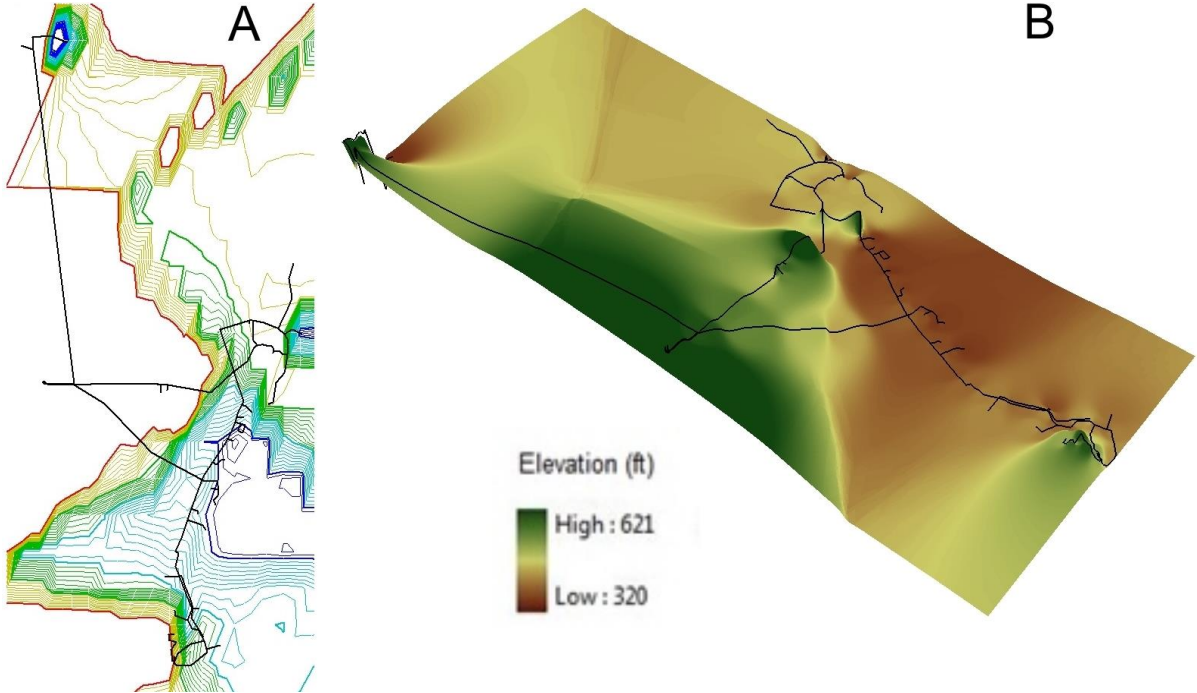
Figure 3.2 Elevation of the study area. A. A contour map is created using the EPANET software B. is produced using the ArcGIS software.

3.4   Data processing

For purposes of this study, the water distribution network is divided into five zones based on the spatial distribution of nodes and the topology of the network which is provided in Figure 3.2.A and B. These zones do not represent pressure zones but geographical zones. In order to understand the initial state of the system effectively, it is first necessary to conduct single time period analysis also called steady state analysis (SSA) of the WDS using the EPANET software before proceeding further with complex simulations. The system is analyzed in flow units of GPM and the Hazen-Williams head loss formula with pipe roughness coefficients ranging between 120 and 140 are used for the simulation. Figure 3.3 illustrates the identified zones together with the result of SSA simulation for the nodal pressure parameter. Note that the water age parameter cannot be obtained with the SSA simulation, since it is a

single time step for the water distribution network. The results of the SSA simulation indicate that the nodal pressure performance of Zone 5 is inadequate as the nodes at the entire zone are under 40 psi. Table 3.1 gives the total base demand and population of each zone in the WDS.
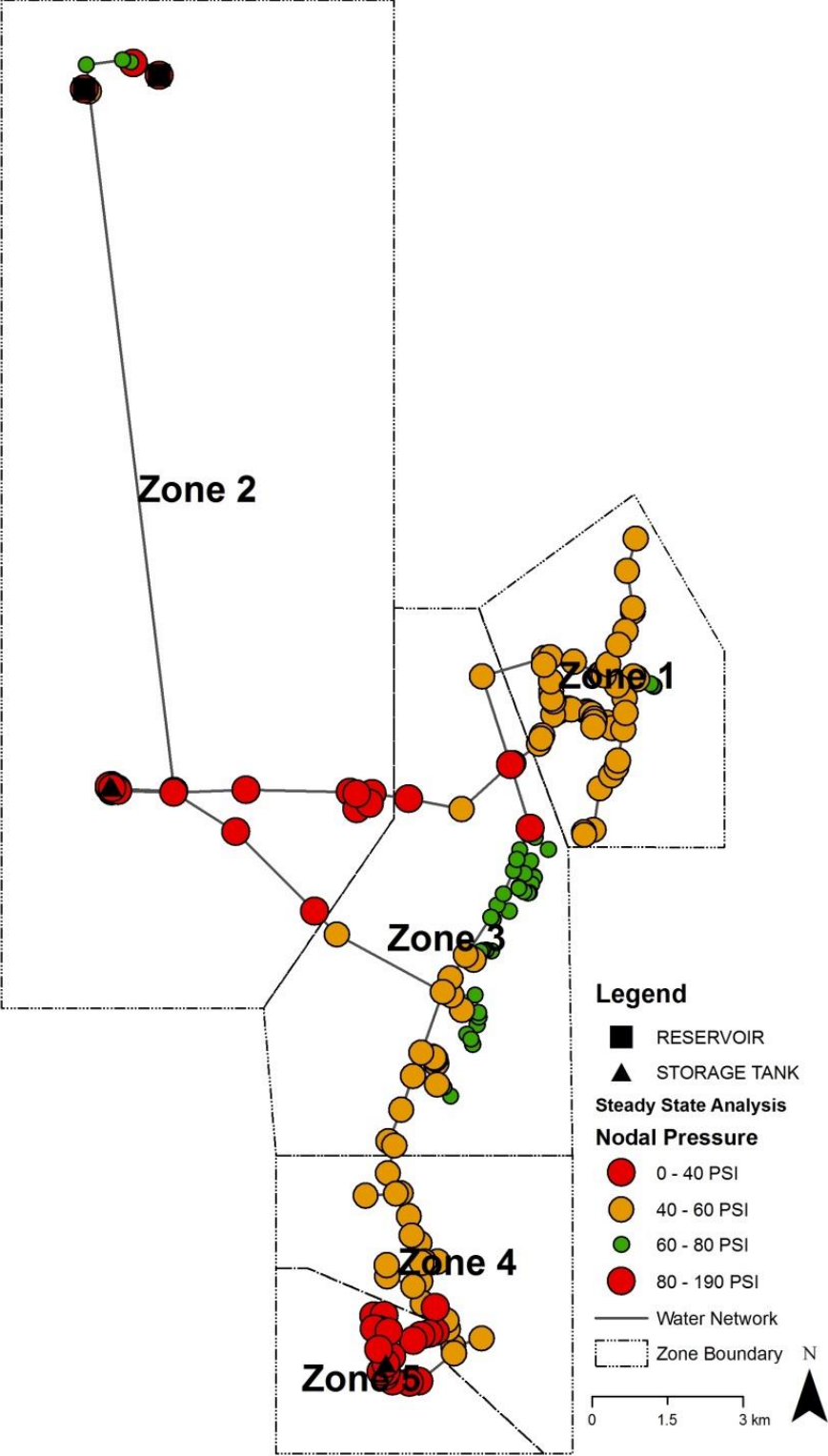
Figure 3.3 Result of the steady state analysis and the location of zones.

Table 3.1. Base demands and population of zones.

Zone	Base demand (GPD)	Population
Zone 1	67,680	376
Zone 2	8,496	47
Zone 3	222,480	1,236
Zone 4	187,732.8	1,043
Zone 5	68,817.6	382
TOTAL	555,206.4	3,084

The EPS is a simulation procedure to observe the behavior of the hydraulic efficiency and water quality in the urban WDSs over an extended period of time (Rossman 2000). In other words, the EPS brings the time dimension into the hydraulic modeling of the urban water network. It enables users to simulate demand variability and understand nodal pressure and water age variations over a certain period of time. For this purpose, a typical demand pattern representing a demand increase from 6 AM to 9 AM and from 5 PM to 8 PM was created which is provided in Figure 3.4-A. For a fire flow simulation in the water network, the demand pattern is modified using the "pattern editor" in the EPANET software in accordance with fire flow requirements (see Figure 3.4-B). In this study, total duration of the EPS is 144 hours (i.e. 7 days); only the 24-hour time period from hours 96 to 119 is taken into account. The reason is that the simulation after a time period contains more realistic results in terms of hydraulics of the WDS.
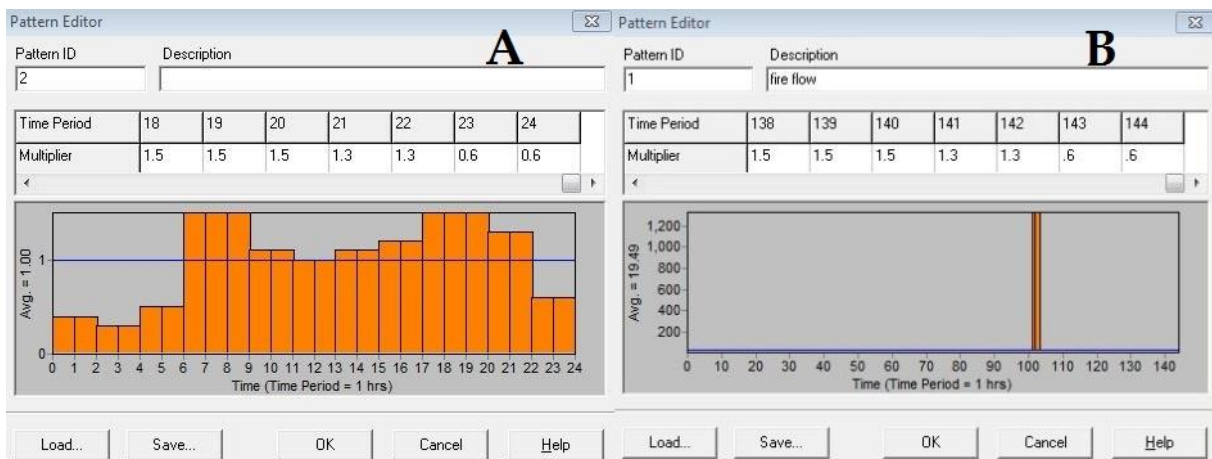
Figure 3.4 A. Demand pattern for the EPSs. B. Demand pattern for the EPSs during fire flow.

The EPANET software uses curves which represent the relationships between two quantities in order to define the behavior and operational characteristics of a WDS. The curves can be created to define pump, efficiency, volume, flow and head loss in the EPANET software. The pump curve is used to model the head and flow rate relationships which represent the nominal speed setting for the pumps in the

EPANET model. The efficiency curve is to control the pump efficiency as a function of pump flow rate. There are two pumps in the current water distribution network located at the close proximity of main reservoirs. The detailed view for the pump locations is given in Figure 3.5.

Pump curves can be defined depending on the number of known flow and head relationships. Depending on the known flow-head parameters, single-point, three-point and multi-point curves can be created using the EPANET curve editor. The EPANET either creates a function to fit into the form (single and three-point curves) or connects points with straight-line segments (i.e. multi-point curve). Pump curves are specific for each pump and can be obtained from the manufacturer. On the other hand, efficiency curves are important to calculate the energy consumption due to pumping water. This curve is created to consider mechanical losses and electrical losses in the pump and pump's motor, respectively (Rossman 2000). Figure 3.6 illustrates efficiency and pump curves that are used in this study. Note that the same efficiency curve is used for both pumps.
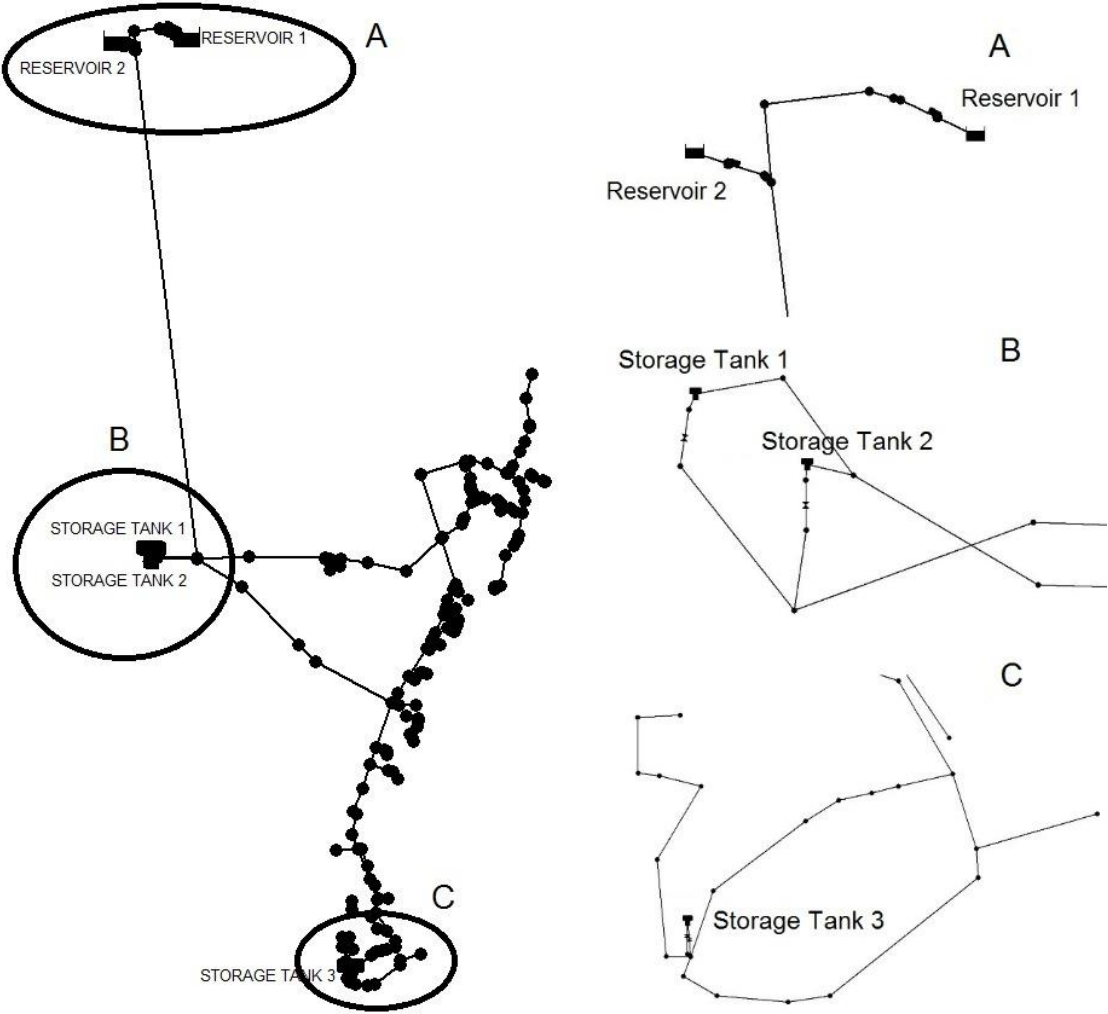
Figure 3.5 The detailed view of pumps and storage tanks in the current WDS.
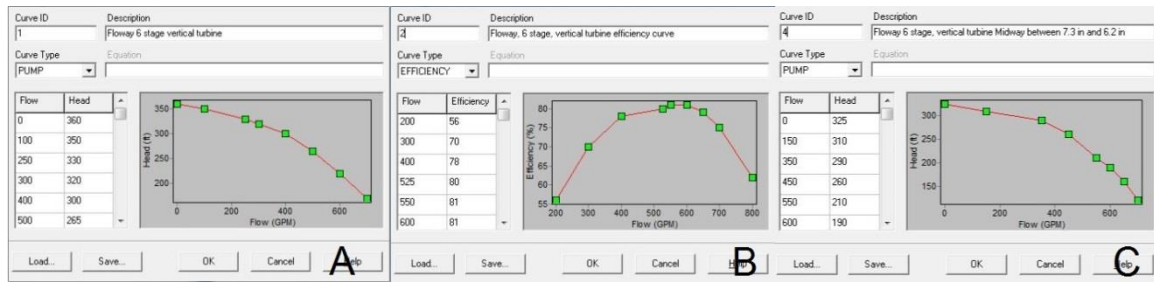
Figure 3.6 Pump and efficiency curves. A. Pump curve for the pump number 1. B. Pump curve for the pump number 2. C. Efficiency curve for pump numbers 1 and 2.

3.5 Conclusion

The main dataset in this dissertation is a vector data set of a water distribution network which is composed of nodes (i.e. point data) and pipes (i.e. line data) and the other network elements such as valves, pumps etc. which are also represented as line segments. The EPANET software is capable of simulating hydraulic efficiency and water quality simultaneously in the WDSs. The sustainability assessment of water networks requires a certain data manipulation and calculation of the EPANET simulation results. This process is completed using the Microsoft Excel software package, since the EPANET software allows users to export the simulation outcomes into a rich text document type file which is compatible with the Microsoft Excel packages. The ArcGIS software has more powerful visualization capabilities than the EPANET software. Therefore, results from the hydraulic efficiency and water quality simulations are stored in the ArcGIS database in order to visualize the data.

CHAPTER 4

METHODOLOGY

4.1 Introduction

This chapter presents an environmental and technical sustainability assessment for centralized and dual WDSs when reclaimed water is used for fire flow and non-potable indoor and outdoor water demand in order to identify current sustainability problems and to propose alternatives (i.e. scenarios) for those identified problems. The proposed methodology is presented in three sections (see Figure 4.1). First, the technical sustainability of an urban WDS is defined and the SI methodology is explained in detail for an urban WDS based upon two parameters: the nodal pressure and water age. Then, environmental sustainability criteria are defined for WDSs. The technical sustainability of baseline scenario is analyzed using the SI methodology and problematic locations of the current water network are identified. Two main approaches are proposed for the identified problems. One is a more traditional approach such as adding new network elements and the other one is using reclaimed water for fire flow and non-potable water demand to increase technical and environmental sustainability. In the final section, technical and environmental sustainability criteria for each scenario are evaluated using the MCDA to compare the feasibility of the scenarios.

4.1.1 Sustainability index for an urban WDS

Two main parameters are used to evaluate the technical sustainability: nodal pressure and water age. The U.S. Environmental Protection Agency EPANET (Rossman 2000) is used for simulating the nodal pressures and water ages throughout the network over time using the EPS. Reliability, resiliency and vulnerability performance criteria introduced by Hashimoto et al. (1982) are used to measure technical sustainability of an urban WDS. A WDS is divided into different geographical zones.
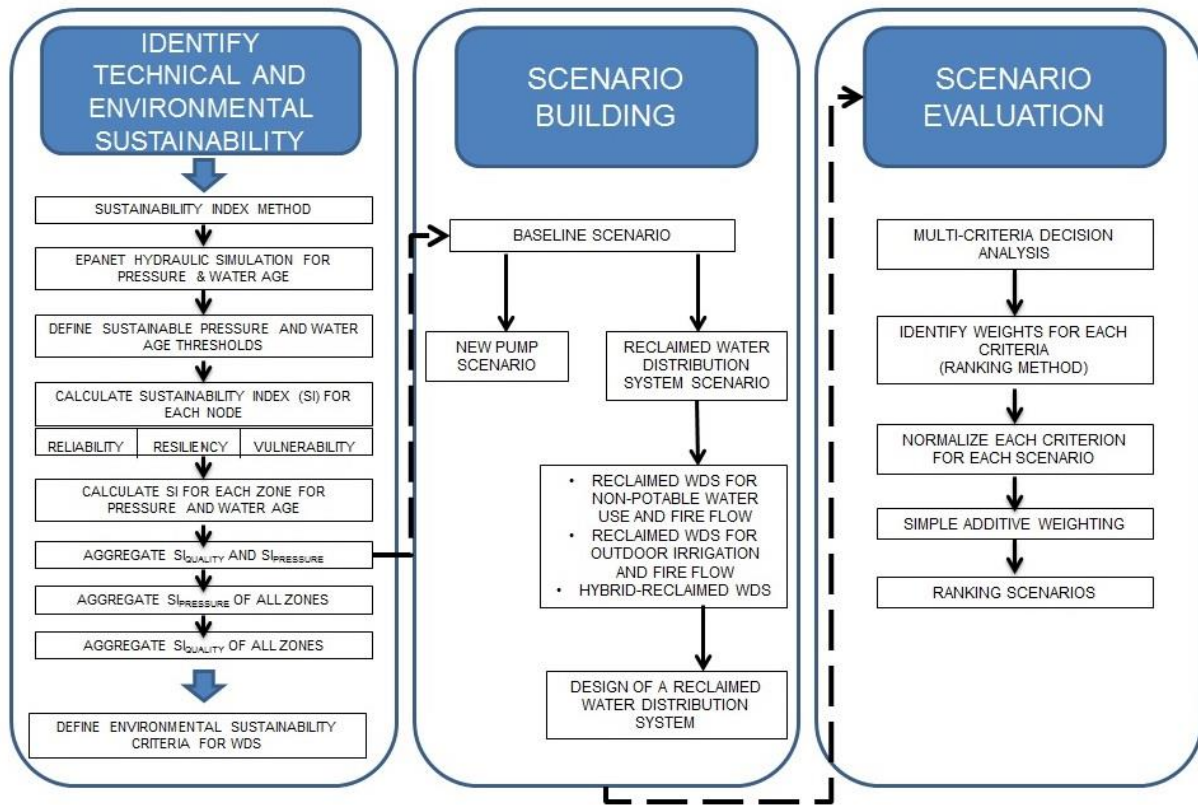
Figure 4.1 Methodology of the study.

The SI in terms of pressure for each zone is calculated by aggregating the entire SI of the corresponding nodes. Similarly, the SI in terms of water age for each zone is obtained by combining sustainability scores of the corresponding nodes. Then, for each zone, sustainability indices in terms of pressure and water age are overlaid in order to produce one overall score. Overall SI scores are used to identify problematic locations in the baseline scenario. Technical sustainability assessments of the proposed alternative scenarios are completed by aggregating the sustainability indices in terms of pressure scores of all zones into one score which represents the overall technical sustainability in terms of nodal pressure for the entire network. Similarly, sustainability indices in terms of water age for all zones are aggregated into one score in order to obtain a single score for the entire network.

4.1.2 EPANET simulation

Hydraulic simulation and water quality analysis are performed using the EPANET model (see section 3.2.1 EPANET software in Chapter 3). The EPS in EPANET software is run for an extended time period such as 7 days (i.e. 144 hours). Only the results from a later 24-hour time period such as hours 96 to 119 are utilized for the SI calculations of the WDS. The main reason of neglecting time steps until the time step 96 is that the EPANET software is solving hydraulics for the first few of days in order

to limit the effects of the beginning simulation assumptions of the network. The simulation after a time period contains more realistic results in terms of hydraulics of the WDS.

4.1.3 Define sustainable pressure and water age thresholds

The nodal pressure is selected as a parameter to assess sustainability in the WDS since it represents water availability at each node which is indirectly related to nodal pressure. Tabesh and Dolatkhahi (2006) emphasized the importance of the nodal pressure in WDSs by stating that the pressure level must be high enough to fully satisfy the users as well as low enough to reduce leakage risk and avoid high operation and maintenance costs. Ozger and Mays (2005) emphasized that the acceptable pressure range in WDSs changes according to the structure of the distribution systems. Therefore, there are no standard pressure scales in literature. Pressure requirements for different locations together with references are given in Table 4.1

Table 4.1 Water pressure requirements.

Reference	Location	Required pressure
Chin 2000	20-story building	120 psi (84.4 mH$_2$O)
	3-story building	42 psi (29.5 mH$_2$O)
U.S. Army Corps of Engineers 1999	Small WDS	20-70 psi (14.1 – 49.2 mH$_2$O)
GLUMB 1992	-	35-60 psi (24.6 – 42.2 mH$_2$O)
Tabesh et al. 2010	Complex network with 1533 connections	15 – 30 mH$_2$O
Swamee and Sharma 2008	High-rise building	Minimum 8 mH$_2$O – 20 mH$_2$O

Swamee and Sharma (2008) stated that the required minimum and maximum nodal pressure range depends on the location and type of the city which changes at each country or state. In this dissertation, upper and lower limits for pressure are identified as 40 psi and 80 psi, respectively. This means that nodal pressure must be in between 40 psi ($\cong$ 28 mH$_2$O) and 80 psi ($\cong$ 56 mH$_2$O) in order to be considered in a satisfactory state. The upper and lower limits that are defined in this dissertation are site-specific and need to be modified with respect to the location and/or identified design requirements.

The water age parameter is representing the overall water quality of the WDSs (Rossman 2000). Similar to the nodal pressure parameter, water age has also system specific requirements (USEPA 2002). For example, based on a survey in US water utilities, minimum and maximum water age are 32 hour and 72 hours, respectively (AWWA and AWWARF 1992). Digiano et al. (2009) stated that the maximum water age is approximately 18 hours in a small scale WDS in North Carolina's Chatham County. In order to assess the SI, the upper limit for water age is set at 24 hours meaning that if water stays in the system more than 24 hours then the performance index of the node is zero. Thresholds for water age are site specific. Decision makers' preferences and expert knowledge need to be considered in order to set the thresholds to calculate technical sustainability of WDSs.

4.1.4 Sustainability index calculation for each node

An SI is a term that indicates the performance of a water system with respect to predetermined thresholds of a satisfactory state (Kay 2000). In order to calculate the performance of the system, the satisfactory state should be differentiated mathematically from the unsatisfactory state. Mathematically the satisfactory and unsatisfactory states are defined as;

$$P_{i,j,t} = \begin{cases} \text{unsatisfactory (0)} & P_{i,j,t} < P_{min} \quad \vee \quad P_{i,j,t} > P_{max} \\ \text{satisfactory (1)} & P_{i,j,t} \geq P_{min} \quad \wedge \quad P_{i,j,t} \leq P_{max} \end{cases} \tag{4.1}$$

where $P_{i,j,t}$ is the pressure at node j in zone i at time t; P_{min} is the minimum pressure; and P_{max} is the maximum pressure. In this dissertation, P_{min} is assumed to be 40 psi ($\cong 28$ m H_2O) and P_{max} is assumed to be 80 psi ($\cong 56$ m H_2O).

Mathematically the satisfactory and unsatisfactory states for water age are defined as;

$$WA_{i,j,t} = \begin{cases} \text{unsatisfactory (0)} & WA_{i,j,t} > WA_{max} \\ \text{satisfactory (1)} & WA_{i,j,t} \leq WA_{max} \end{cases} \tag{4.2}$$

where $WA_{i,j,t}$ is the water age at node j in zone i at time t; WA_{max} is the maximum water age allowed. In this dissertation, WA_{max} is assumed to be 24-hour.

The SI is a weighted combination of reliability, resiliency, and vulnerability which may change over time and space (Loucks 1997). The definitions of reliability, resiliency, and vulnerability were proposed by Hashimoto et al. (1982) and given in **the** following.

Reliability (REL) is the probability that the WDS is in a satisfactory state defined as

$$REL_{k,i,j} = \frac{\text{\# of times satisfactory occurs}}{\text{total \# of time steps}} \qquad (4.3)$$

where k refers to nodal pressure or water age at node j in zone i.

Resiliency (RES) represents how fast the system recovers from a failure defined as

$$RES_{k,i,j} = \frac{\text{\# of times satisfactory follows unsatisfactory}}{\text{total \# of times unsatisfactory occurs}} \qquad (4.4)$$

Vulnerability (VUL) is the magnitude or duration of an unacceptable state of WDS in a certain time scale. Kay (2000) stated that the vulnerability could be measured by dividing the cumulative extent of unsatisfactory values to the sum of all values in the simulation period. This evaluation method is also used by Huizar et al. (2011) in order to create a DSS for water supply sustainability. In this dissertation, vulnerability is defined as

$$VUL_{k,i,j} = \frac{\sum \text{unsatisfactory values}}{\sum \text{all values}} \qquad (4.5)$$

The following SI definition proposed by Sandoval-Solis et al. (2011), to determine sustainability of water management policies for the Rio Grande Basin, is used to calculate the SI for WDSs.

$$SI_{k,i,j} = \left[REL_{k,i,j} * RES_{k,i,j} * \left(1 - VUL_{k,i,j} \right) \right]^{1/3} \qquad (4.6)$$

The main feature of the SI is that it ranges from 0 (i.e. the lowest degree of sustainability) to 1 (highest degree of sustainability). Another property is that if any one of the performance criteria of reliability and resiliency is zero and the performance criteria of vulnerability is one then the overall SI will be zero.

4.1.5 Sustainability index calculation for each zone

So far the methodology is explained for the SIs of pressure and water age for each node. The next step is to evaluate the performance of each zone. In this dissertation, the WDS is divided into different geographical zones based on the spatial distribution of nodes. For this purpose, each node is weighted with its demand. This

weighting procedure is essential to identify the population effected by poor performance of the WDS. If one node has relatively high demand, its SI will influence the overall sustainability of a zone. Sustainability indices of zones are important to identify problematic locations in WDSs.

The following function is used to calculate the SI of each zone.

$$SI_{k,i} = \frac{\sum_{j=1}^{NJ_i} D_{i,j,daily} \; SI_{k,i,j}}{\sum_{j=1}^{NJ_i} D_{i,j}} \qquad (4.7)$$

where k refers to pressure or water age, $SI_{k,i}$ is the SI in terms of pressure (k = pressure) or water age (k = waterage) in zone i, NJ_i is the total number of nodes in zone i, $SI_{k,i,j}$ is the SI in terms of pressure or water age at node j in zone i, and $D_{i,j,daily}$ is the daily demand of node j in zone i.

4.1.6 Overall sustainability index calculation

Overall SI is calculated in order to identify the problematic regions in the baseline scenario. Sustainability indices for each zone in terms of pressure and water age are aggregated to produce one overall score of sustainability using the simple weighted additive technique which is defined as; . The following function is used to calculate the SI_overall score.

$$SI_{overall,i} = \sum_{k=1}^{n} w_{k,i} SI_{k,i} \qquad (4.8)$$

where $SI_{overall,i}$ is the overall SI of the i-th zone, $SI_{k,i}$ is the SI of the i-th zone with respect to the k-th attribute, k is the individual index (i.e. nodal pressure and water age) and the $w_{k,i}$ is the normalized weight (i.e. $\sum w_{k,i} = 1$) (Malczewski 1999). In this dissertation, it is assumed that the parameters pressure and water age are equally important, therefore, weights are distributed evenly between parameters. However, based on decision makers' preferences, weights could be distributed differently to prioritize a certain criteria (i.e. nodal pressure or water age). As mentioned before, the SI_overall scores are used to identify problematic locations in the baseline scenario.

4.1.7 Technical sustainability calculation for the water network

In order to compare each scenario, the sustainability indices in terms of nodal pressure for each zone are aggregated into the technical sustainability score of the water network. Similarly, the sustainability indices in terms of water age for each

zone are combined into the technical sustainability score of the water network for water age. Equation 9 is used to obtain technical sustainability scores for the nodal pressure and water ages.

$$SI_{network,k} = \frac{\sum_{i=1}^{r} SI_{k,i}}{r} \qquad (4.9)$$

where $SI_{network,k}$ is the technical sustainability score of the entire network of k (i.e. pressure or water age), r is the total number of zones in the water network.

4.2 Define environmental sustainability criteria for urban WDSs

In order to analyze the scenarios, environmental sustainability criteria are identified based on the related literature review. Criteria are the set of factors which may be used to evaluate the alternatives with respect to their relative sustainability. This evaluation can be used to support decision-making, to compare decision alternatives, strategies and ideas (Singh et al. 2012). Foxon et al. (2002) proposed a sustainability assessment methodology for the decision-making process in the UK water industry. Sustainability criteria are categorized into economic, environmental, social, and technical sections. The annual freshwater withdrawal and energy use for water supply are categorized as environmental criteria. In a more recent study, a DSS was proposed for sustainable planning of urban water systems. Total energy consumption together with total water use and water reuse was considered as environmental indicators of sustainability (Willuweit and O'Sullivan 2013). In this dissertation, hydraulic efficiency and water quality measures in an urban WDS are assessed over time using SI methodology. In addition, energy intensity and total fresh water use are selected as sustainability criteria to compare alternatives.

4.2.1 Energy intensity

Energy intensity is defined as the total amount of energy required to use a certain amount of water in a specific location (Wilkinson 2007). The energy intensity is calculated as follows:

$$\text{ENERGY INTENSITY} = \frac{\text{total energy consumption in the network in each time step (KWH)}}{\text{total demand in each time step (KGal)}} \qquad (4.10)$$

The EPANET software provides pumping energy and cost computations based on specified values (i.e. pump curves and pump efficiency curves). The results can be displayed on an "Energy Report", which also provides statistical values about the

energy consumption of each pump. An example of an energy report is given in figure 4.2. In addition to energy intensity, users are able to observe average efficiency of pumps, average energy consumption of the pumps (i.e. Average Kwatts), peak energy consumption of pumps (Peak Kwatts) and the cost per day. In this dissertation, energy intensity is identified as environmental criteria. Therefore, the energy intensity as a unit of Kw-hr/Mgal is taken from the energy report of the EPANET software for each scenario in this dissertation.

Pump	Percent Utilization	Average Efficiency	Kw-hr /Mgal	Average Kwatts	Peak Kwatts	Cost /day
10	58.33	75.00	314.07	62.01	62.73	0.00
335	29.51	75.00	394.83	309.49	310.86	0.00
Total Cost						0.00
Demand Charge						0.00

Figure 4.2 EPANET software example energy report (Rossman 2000).

4.3   Scenario building

The current urban WDS is analyzed in terms of defined technical sustainability. Once the problems with the current water system are identified for current population and water demand, two alternative scenarios are proposed. One is based upon adding new network components to overcome the sustainability issues. The other one involves introducing a reclaimed WDS for the fire flow and the non-potable water use.

4.3.1   Scenario I: baseline

Main purpose of the baseline scenario is to identify the current problems in an urban WDS. The proposed technical sustainability assessment methodology is applied to a water network using current water demands and problematic locations (i.e. zones) in terms of the technical sustainability are identified. Once the $SI_{overall}$ for each zone is calculated, the $SI_{overall}$ (i.e. [0, 1]) is divided into four categories: unacceptable, moderate, acceptable and ideal range. In this dissertation, if the overall sustainability score of a zone is in the "unacceptable" state, then the zone is assumed to be unsustainable and alternative scenarios are proposed to increase the sustainability conditions at this zone. The SI range and the corresponding decision rules is given in Table 4.2.

Table 4.2 The overall SI for zones.

SI range	State
0-0.25	Unacceptable
0.25-0.5	Moderate
0.5-0.75	Acceptable
0.75-1	Ideal

4.3.2   Scenario II: new pump scenario

A new pump scenario is a more traditional approach in order to resolve the identified technical problems in the baseline scenario. Therefore, new network components such as booster pumps, valves, and storage tanks are added into the urban WDS to increase the technical sustainability score of the entire network under fire flow condition. Once the necessary modifications are completed, fire flow simulations are applied to verify the technical sustainability under fire event. The ISO (2008) minimum fire flow requirements are used to simulate the fire flow in the modified water network (i.e. 1,000 GPM for two hours and the minimum nodal pressure requirement is at least 20-psi). Technical sustainability scores as well as environmental sustainability criteria (i.e. total freshwater use, energy intensity) are evaluated for the entire network in this scenario.

4.3.3   Scenario III: reclaimed water for fire flow scenarios

In this scenario, a decentralization approach is applied to zones with the "unacceptable" technical sustainability scores. Specifically, a separate WDS is designed to satisfy non-potable indoor and outdoor water demands while the existing water network serves for potable water demands. Four different scenario options are considered under the reclaimed water distribution scenario: using a non-potable water network for non-potable water demand (option A), using a non-potable WDS for only outdoor irrigation and fire flow (option B), using a hybrid system for fire flow (i.e. fire flow demand should be satisfied using both potable and non-potable WDS) and a non-potable water network for non-potable water demand (option C), using a hybrid system for fire flow and a non-potable water network for only outdoor irrigation (option D). Water demand assumptions based on the percentage of base demands for each option are given in Table 4.3. Residential water use categories can be found in Metcalf and Eddy (2003). In this dissertation, the non-potable water demand in Scenario III options A and C is identified as toilet flushing and cleaning, outdoor irrigation and fire flow.

Table 4.3 Assumptions of water demand for the reclaimed WDS scenario.

Options	Percentage of total base demand in the reclaimed WDS	Percentage of total base demand in the potable WDS	Total fire flow in the reclaimed WDS	Total fire flow in the potable WDS
Option A	75%	25%	1,000 GPM for 2 hours	-
Option B	30%	70%	1,000 GPM for 2 hours	-
Option C	75%	25%	500 GPM for 2 hours	500 GPM for 2 hours
Option D	30%	70%	500 GPM for 2 hours	500 GPM for 2 hours

A dual WDS is designed to meet the non-potable water demand on the zones with the "unacceptable" technical sustainability scores. A linear optimization approach is used to design a reclaimed WDS. The details of the optimization approach are explained in the following section. The proposed technical sustainability assessment methodology is applied to a potable WDS as well as a non-potable water network. Finally, fire flow is added to each scenario option and the technical and environmental sustainability of the reclaimed water network is investigated under fire event.

4.3.4 Design of the non-potable WDS

The planning and design considerations of a dual WDS (i.e. non-potable WDS) are similar to potable WDSs. Asano et al. (2007) explains details of the design requirements for reclaimed WDSs. Design characteristics that are considered in this study are given in Table 4.4.

According to Asano et al. (2007), cross connections of non-potable and potable networks should be avoided while designing reclaimed WDSs due to the contamination risk. If cross connections cannot be avoided, a dual network should be operated at low pressures. In addition, when there is a need to install the non-potable pipeline crossing over a potable WDS, then the pipes in the non-potable WDS should be steel pipe with at least 6 m long in order to prevent any contamination.

In this dissertation, a tree structure layout for the reclaimed WDS is proposed to minimize any cross connections. The non-potable water network is designed using a linear programming optimization approach in order to minimize the cost of piping and pump head. The optimization approach is explained in detail in the following section.

Table 4.4 Design considerations of the reclaimed WDSs (adapted from Asano et al. 2007).

WDS components	Characteristics	Detail information
Piping Network	Loop	Minimum horizontal separation of 3 m from the potable WDS
	Grid	At least 0.3 m deeper than the potable WDS
	Tree	At least 6 m steel pipe casting required at the intersection with the potable WDS
Storage	Short Term Storage	Steel or concrete tanks, elevated steel tanks, ground-level reservoirs at an elevated site
	Long-Term Storage	Reservoirs, lakes
Pumping station	Located at the water reclamation plant	-
Pipe material	Ductile iron, steel, polyvinylchloride (PVC), high-density polyethylene	-

4.3.4.1 *Optimization approach for the design of the reclaimed WDS*

An optimization model was developed for the design of a reclaimed WDS. Because the non-potable WDS is dendritic, a LP approach can be utilized and adapted from Mays and Tung (1992). Linear programming is an optimization approach that is based upon a linear objective function and a set of linear constraints. Linear programming has been applied extensively in the field of water resources engineering as provided by Lansey (2006).

Linear programming is applied herein to determine the minimum cost pipe sizes and pumping heads of the dual water network. The General Algebraic Modeling System (GAMS 2014)) was used as the solver for the optimization model developed. This is a high-level modeling system for mathematical programming and optimization, consisting of a language compiler and a number of integrated high-performance solvers. The GAMS can be used for modeling linear, nonlinear and mixed integer optimization problems and is designed for complex, large scale modeling applications, and allows building large maintainable models that can be adapted quickly to new situations.

4.3.4.2 *Optimization model*

An optimization model consists of an objective function and a set of constraints. The objective function of the optimization model is to minimize the sum of costs of the piping network and the pumping, expressed as

$$\text{Minimize } Z = \sum_{(i,j) \in I} \sum_{m \in M_{i,j}} C_{i,j,m} X_{i,j,m} + \sum_k CP_k XP_k \tag{4.11}$$

where *i* is the set of pipe links; $M_{i,j}$ is the set of candidate pipe diameters for the pipe connecting nodes *i* and *j*; $C_{i,j,m}$ is the cost per unit length of the *m*-th diameter for the link connecting nodes *i* and *j*; $X_{i,j,m}$ is the unknown length of pipe segment of the *m*-th diameter in the pipe reach between nodes *i* and *j*; CP_k is the unit cost of pumping head at location *k*; and XP_k is the unknown pumping head at location *k*. The decision variables are $X_{i,j,m}$ and XP_k.

Subject to the following constraints:

1. Length constraints for each link;

$$\sum_{m \in M_{i,j}} X_{i,j,m} = L_{i,j} \qquad\qquad (i,j) \in I \tag{4.12}$$

where $L_{i,j}$ is the length of the link connecting nodes *i* and *j*.

2. Conservation of energy constraints written from the source node with known elevation, H_s, to each of the delivery points.

$$H_{min,n} \leq H_s + \sum_k XP_k - \sum_{(i,j) \in I_n} \sum_{m \in M_{i,j}} J_{i,j,m} X_{i,j,m} \leq H_{max,n} \tag{4.13}$$
$$n = 1, \dots, N$$

where $H_{min,n}$ and $H_{max,n}$ are the minimum and maximum allowable heads at delivery point *n* and *N* is the total number of delivery points.

3. Non-negativity constraints;

$$X_{i,j,m} \geq 0 \tag{4.14}$$

$$XP_k \geq 0 \tag{4.15}$$

4.3.5 Scenario evaluation for future demand and population

4.3.5.1 Future population and demand management alternatives

There are various factors that can influence the water consumption per person such as climate, socio-demographic features, water efficient devices, water quality, and nodal pressure at WDSs, the extent of water metering, water resource availability, and population changes (Duggal 1989, Willis et al. 2013). In order to identify future water demand growth, not only the population growth but also spatial expansion of urban areas should be considered for planning future water infrastructure (Rao 2005). There is an uncertainty involved in predicting the urban expansion which depends on distance to other urban infrastructure facilities (i.e. distance to major roads, bus stops, city amenities), topography of the region, current land use and population density (Rao 2005). In this dissertation, due to the lack of data, the urban development and expansion are neglected in this case study for future scenarios but focused on population variations for future sustainable water infrastructure plans.

For population variation, two separate objectives are tested on the case study. One is to analyze the changes in the water infrastructure when the water demand decreases and the other one is representing a more general problem of increasing population and water demand. The population forecasts for Germany and the USA specifically Arizona state examples are considered to represent the population and water demand decrease and increase, respectively. Table 4.5 provides information for the current and future populations in Germany and the USA.

Table 4.5 Population projections for the USA and Germany.

Country/ State	Reference	Year and population	2050 population forecast	Percentage change
Germany	World bank 2014	2015-81,081,000	69,717,000	-14.02%
	Federal Statistical Office 2006	2013-80,716,000	69,400,000	-14.01%
USA	World bank 2014	2015-321,428,000	392,821,000	+22.52%
	US census bureau 2012	2015-321,363,000	399,803,000	+24.4%
Arizona	Arizona department of administration 2014	Low 2015 - 6,713,000	9,707,500	+44.60%
		Medium 2015 – 6,777,500	11,562,500	+70.60%
		High 2015 – 6,830,600	13,163,800	+92.71%

According to the Natural Resources Defense Council (2010), water demand in the USA will increase in accordance with the population increase. Total water demand is expected to increase up to 12.3 % in 2050. This increase is projected to be 25 % in arid regions such as Arizona, New Mexico, and Florida etc. On the other hand, water demand is likely to decrease up to 9% by 2030 in Kaiserslautern, Germany and adjacent areas called "Westpfalz" (Roth 2008).

In addition to population increase or decrease, future water demand can be managed through different water demand management alternatives. For example, water saving devices, pricing, abstraction charges and taxes, public awareness campaigns and regulatory changes could contribute to current and future water demand saving. Specifically, through water saving devices such as low-flow toilets, water efficient washing machines, taps with air devices etc., residential water demand could be reduced by 41 % (OECD 2011). Water efficiency devices might be expensive for the public. Local authorities could grant subsidies for the public to facilitate the transition to water saving devices. In New York, through financial support, 1.3 million toilets were replaced with the low flow toilets which resulted in up to 37 % water demand reduction between 1994 and 1997. As a result, water saving devices could assist to mitigate the rate of future water demand growth (EPA 2002). In another example, in Albuquerque, New Mexico, using high efficient toilets, landscape irrigation as well as with new water pricing and public education policies, water demand was reduced up to 14% between 1990 and 2001 (EPA 2002). With the technological innovations and further implementation policies, water consumption per person could be reduced around the world by 2050. Examples of the amount of water that could be saved using water efficient appliances are given in Table 4.6.

Table 4.6 Potential water savings from water efficient appliances.

Reference	Application		Demand decrease (%)
Makropoulos et al. 2008	Water saving devices		35 %
Dworak et al. 2007	Toilet flushing		32-55 %
	Shower		33-44 %
	Bath		26 %
	Taps		15 %
	Washing machine		33-25 %
	Dish washer		30-40 %
	Total		29-41 %
Read 2005	Toilets, dish washers, washing machines		20-30 %
Sharma et al. 2009	Kitchen, bathroom, toilet, laundry, outdoor	Improved demand management	Approximately 15 %
		Highest demand management	Approximately 43 %

Table **4.6** Cont'd

Lee et al. 2011	High efficiency shower head	Approximately 11 %
	High efficiency toilets	Approximately 13 %
	High efficiency washing machines	Approximately 15 %
AWWA 2013	Low-flow plumbing fixtures and water-efficient appliances such as dishwashers and washing machines	15-25 %

4.3.5.2 *Assumptions for the future population scenarios*

For demonstration purposes in this dissertation, water demand assumptions for 2050 are given in Figure 4.3. Water consumption per person is assumed to reduce by 10 % based upon the use of water efficient appliances in the population and water demand increase scenarios. The changes in the technical and environmental sustainability of an existing water distribution network are evaluated considering both population increase and decrease options. For the population increase scenarios, it is assumed that the population and water demand will increase by 25 % in 2050 while the future water consumption per person is assumed to be 162 GPD as compared to the 180 GPD in the current system scenarios.

In addition to population increase scenarios, the baseline, new pump, and reclaimed water for fire flow scenarios are also evaluated under the assumption of 10 % reduction of population and water demand in 2050. In this case, total population would be 2775 in the future and the water consumption per person is 180 GPD. Both the population and water demand are increased and decreased linearly for all the nodes of the WDS. Sprawling urban development or expansion of WDS is neglected due to the unavailability of the data.
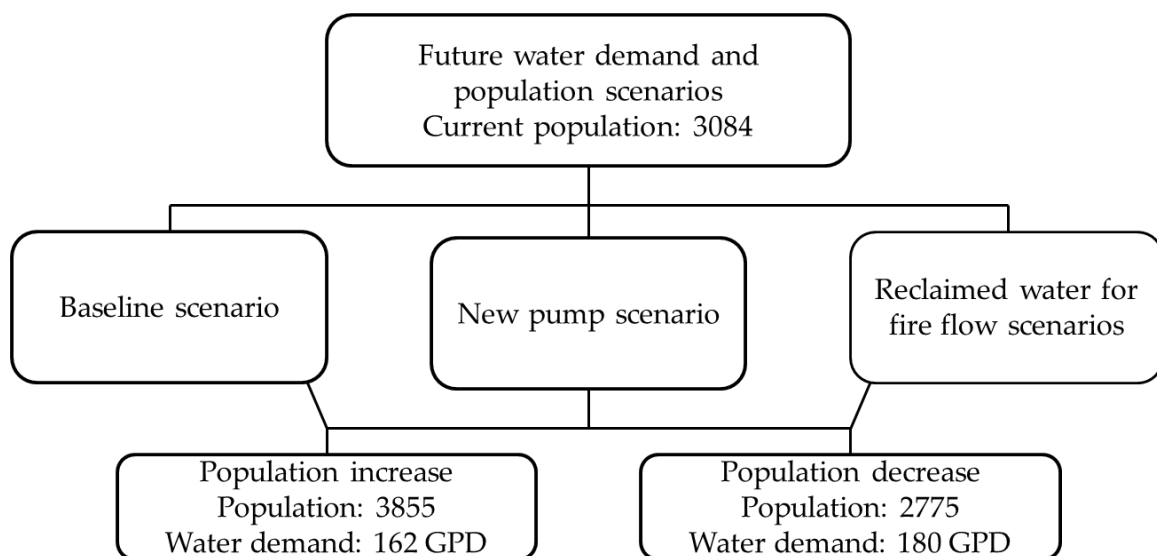
Figure 4.3 Future population and demand management assumptions.

In addition to the water demand changes, diameters of the pipes have been modified in each future water network scenario. Since the water mains will deteriorate in time and need to be replaced. In order to identify pipes that need replacement, the average velocities at each pipe in each scenario are investigated. According to Savic et al. (2011), peak velocities should be above 0.6 - 0.8 m/s (circa 1.97 – 2.6 f/s) to be able to prevent any sediment-based water quality issues. If the peak velocity at a pipe is less than 0.3 - 0.4 m/s (circa 0.98 – 1.3 f/s), the sediment accumulation is possible. In another study, penalty curve for velocities of the pipes are identified in order to create a prioritization modal for the rehabilitation of WDSs (Tabesh and Saber 2012). The velocities of the pipes that are less than 0.15 m/s (circa 0.49 f/s) are identified as unsatisfactory in Tabesh and Saber (2012).

Therefore, average velocities of the pipes are calculated using the modified water demands for the future scenario options (i.e. population and water demand increase or decrease). If the average pipe velocity is less than 0.15 m/s (circa 0.49 f/s), the diameter of the corresponding pipe is decreased to the next commercial size. For example, if the average velocity of a pipe is 0.15 m/s (circa 0.49 f/s) and the diameter of the pipe is 8-inch, then for the future scenario, the diameter is decreased to 6-inch.

4.4 Scenario evaluation

4.4.1 Multi-criteria decision analysis

The MCDA is used to evaluate and compare the feasibility of each scenario based on the identified technical and environmental sustainability criteria. In order to compare criteria of each alternative scenario, the technical and environmental sustainability criteria are normalized using the linear transformation methodology. A simple weighted additive methodology is used for aggregating the criteria. Weights are calculated using the "rank sum" method and assigned to the each normalized attribute.

4.4.2 Normalization of each criterion

Normalization is a necessary procedure when the criteria in decision processes have different units and dimensions (Hebert and Keenleyside 1995). In this dissertation, a linear scale transformation methodology is applied to each criterion in order to assign normalized scores to the raw data (i.e. technical sustainability scores for pressure and for water age, total fresh water use, and energy intensity). There are a number of linear scale transformation methodologies described in literature, the "maximum score" and the "score range procedures" are the most frequently used producers (Malczewski 1999). Even though "maximum score" provides equal order of magnitude of the standardized scores, the minimum value among several criteria does not necessarily have to be zero. This means that while the maximum value

among the attributes will be the maximum standardized value (i.e. equal to 1), however, the minimum value may still get a certain value. In this dissertation, the "score range procedure" is applied to normalize the technical and environmental sustainability criteria of each scenario which provides values in a range of 0 to 1. The following formula is used in this procedure.

$$y'_{ij} = \frac{y_{ij} - y_j^{min}}{y_j^{max} - y_j^{min}} \tag{4.16}$$

$$y'_{ij} = \frac{y_j^{max} - y_{ij}}{y_j^{max} - y_j^{min}} \tag{4.17}$$

Where y'_{ij} is the normalized score for the *i*th scenario and the *j*-th criterion, y_{ij} is the raw value, y_j^{min} is the minimum score for the *j*-th criterion, y_j^{max} is the maximum score for the *j*-th criterion. The main advantage of this procedure is that normalized scores range from 0 to 1, 0 is the worst score and 1 is the best score (Malczewski 1999). Equation 4.16 (i.e. benefit criterion) is used for sustainability indices for water age and pressure in order to maximize the benefits from the criteria. Equation 4.17 is called "cost criterion" and applied to energy intensity and total fresh water use.

4.5.3. Defining weights for each criterion

The weighting algorithms represent the importance of each criterion with respect to decision makers' preferences. Fundamentally, decision makers rank each criterion either by using straight ranking (i.e. the most important criterion is placed on the first ranking) or inverse ranking (i.e. the least desirable criterion is placed on the first ranking) based on their consideration (Malczewski 1999). After the ranking procedure is completed by decision makers, weighting algorithms are used to generate numerical weights for each rank-order. There are several weighting algorithms in literature that can be found in Figueira et al. (2005). Rank sum, rank reciprocal, and the rank exponent methods are the most commonly used algorithms for generating numeric weights (Malczewski 1999). In this dissertation, weights are calculated using the "rank sum" algorithm given in following formula.

$$w_j = \frac{n - r_j + 1}{\sum (n - r_k + 1)} \tag{4.18}$$

where w_j is the normalized weight for the *j*-th criterion, *n* is the number of criteria (i.e. technical sustainability for pressure or for water age, total fresh water use, and energy intensity) and r_k is the ranked position of the criterion (Malczewski 1999). In

this dissertation, several ranking options are considered in order to reflect different priorities in the decision-making process. Table 4.7 gives the ranked order of each criterion while Table 4.8 provides the numerical weights for the environmental and technical sustainability criteria based on the ranked order.

Table 4.7 Ranked order for environmental and technical sustainability criteria.

Criteria	Rank 1	Rank 2	Rank 3	Rank 4
$SI_{network,pressure}$	1	2	3	3
$SI_{network,waterage}$	2	1	4	4
Total Fresh Water Use	3	3	1	2
Energy Intensity	4	4	2	1

Table 4.8 Numerical weights for environmental and technical sustainability criteria.

Criteria	Weights for Rank 1	Weights for Rank 2	Weights for Rank 3	Weights for Rank 4
$SI_{network,pressure}$	0.4	0.3	0.2	0.2
$SI_{network,waterage}$	0.3	0.4	0.1	0.1
Total Fresh Water Use	0.2	0.2	0.4	0.3
Energy Intensity	0.1	0.1	0.3	0.4

There are 4 main criteria for each scenario in order to assess the technical and environmental sustainability of urban WDSs. Ranking options 1 and 2 in Table 4.7 emphasize the importance of technical sustainability in the urban WDS therefore; technical sustainability scores for nodal pressure and water age parameters (i.e. $SI_{pressure}$ and $SI_{waterage}$ respectively) are ranked in higher orders. On the other hand, the third and fourth ranking options prioritize the environmental sustainability criteria. In the third ranking option, total fresh water use is given the first order and energy intensity is given the second place. The energy intensity criterion is the most important criterion in the fourth ranking option which also emphasizes the significance of the environmental sustainability in the urban WDSs. Although there are other ranking combinations for these criteria, the proposed ranking options are sufficient to evaluate scenarios in this dissertation. Results of the MCDA for each ranking option will assess the scenarios with respect to changing the importance of each criterion. Decision makers should decide which criterion is more important and the result of the scenario evaluation will change accordingly.

4.4.3   Simple additive weighted methodology

Simple weighted additive methodology also known as "weighted linear combination" is the most commonly used multi-criteria decision algorithm to evaluate decision alternatives. Basically, in this methodology final scores are given to each alternative by multiplying the weights of each criterion in each alternative by its normalized scores. Once final scores are obtained for each alternative, the highest score among all alternatives is selected as a result. The following decision rule is applied to each scenario.

$$A_l = \sum_m w_m S_{l,m} \qquad\qquad\qquad (4.19)$$

where w_m is the normalized weight (i.e. $\sum w_m = 1$), $S_{l,m}$ is the normalized score of the l-th scenario with respect to m-th criterion, A_l is the total score of the l-th scenario (Malczewski 1999). Decision makers may assign weights to each criterion based on their preference of importance. As an alternative, the weights are calculated and assigned using weighting algorithms. As explained in detail before, in this research, weights are identified using the ranking methodology.

4.5   Conclusion

This chapter presents an environmental and technical sustainability assessment methodology for centralized and dual WDS under fire flow scenarios to identify current sustainability problems and to propose solutions (i.e. scenarios) addressing the identified problems. Table 4.9 summarizes all scenario options that are proposed in this dissertation and will be examined in the following chapters.

The SI assessment using reliability, resiliency, and vulnerability performance criteria is used to define technical sustainability of potable and reclaimed water networks. EPANET software is used to carry out hydraulic and water quality simulations in the water network. Nodal pressure and water age are identified as main parameters to represent hydraulic efficiency and water quality in water networks, respectively. Resource utilization (Foxon et al. 2002) such as total fresh water use in an urban WDS, and total energy intensity are considered as environmental sustainability criteria.

The MCDA is one of the most used methods to combine multiple criteria, especially if there is certain numbers of alternatives to be evaluated in the decision-making process (Fontana et al. 2013, Singh et al. 2012). In this study, technical and environmental criteria for an urban WDS are aggregated for each scenario using the Simple Additive Weighting Method.

Table 4.9 Summary of the proposed current and future WDS scenarios.

SCENARIO	NAME	MODIFICATION		
Scenario I	Baseline	No modification of an existing WDS		CURRENT SYSTEM SCENARIOS
Scenario II	New Pump	Improve sustainability and the technical performance by adding network elements		
Scenario III	Reclaimed Water for Fire Flow	Requires additional WDS to meet non-potable water demand	Option A: Using reclaimed water for non-potable indoor and outdoor water demand and for fire flow	
			Option B: Using reclaimed water for outdoor water demand and for fire flow	
			Option C: Using reclaimed water for non-potable indoor and outdoor water demand. Using potable and reclaimed water for fire flow	
			Option D: Using reclaimed water for outdoor water demand. Using potable and reclaimed water for fire flow	
Scenario IV	Baseline	Increasing water demands at the nodes and decreasing pipe diameters		INCREASING WATER DEMAND AND POPULATION ASSUMPTION
Scenario V	New Pump	Increasing water demands at the nodes and decreasing pipe diameters. Adding network elements in order to meet the increased water demands such as booster pumps, valves etc.		
Scenario VI	Reclaimed Water for Fire Flow	Increasing water demands at the nodes and decreasing pipe diameters. Requires additional WDS to meet non-potable water demand	Option A: Using reclaimed water for non-potable indoor and outdoor water demand and for fire flow	
			Option B: Using reclaimed water for outdoor water demand and for fire flow	
			Option C: Using reclaimed water for non-potable indoor and outdoor water demand. Using potable and reclaimed water for fire flow	
			Option D: Using reclaimed water for outdoor water demand. Using potable and reclaimed water for fire flow	

Table 4.9 Cont'd

Scenario VII	Baseline	Decreasing water demands at the nodes and decreasing pipe diameters		DECREASING WATER DEMAND AND POPULATION ASSUMPTION
Scenario VIII	New Pump	Decreasing water demands at the nodes and decreasing pipe diameters.		
Scenario IX	Reclaimed Water for Fire Flow	Decreasing water demands at the nodes and decreasing pipe diameters. Requires additional WDS to meet non-potable water demand	Option A: Using reclaimed water for non-potable indoor and outdoor water demand and for fire flow	
			Option B: Using reclaimed water for outdoor water demand and for fire flow	
			Option C: Using reclaimed water for non-potable indoor and outdoor water demand Using potable and reclaimed water for fire flow	
			Option D: Using reclaimed water for outdoor water demand. Using potable and reclaimed water for fire flow	

CHAPTER 5

VISUALIZATION APPROACH

5.1   Introduction

The main components of WDSs are nodes (represented as point data) and pipes (represented as polylines). Generally, the nodal pressure and water age parameters are measured at the nodes while the pipes connect the nodes and have hydraulic parameters such as velocities, head losses, etc. associated. The visualization methodology steps are explained in detail in this chapter. Figure 5.1 illustrates the main procedures that are followed in this study.
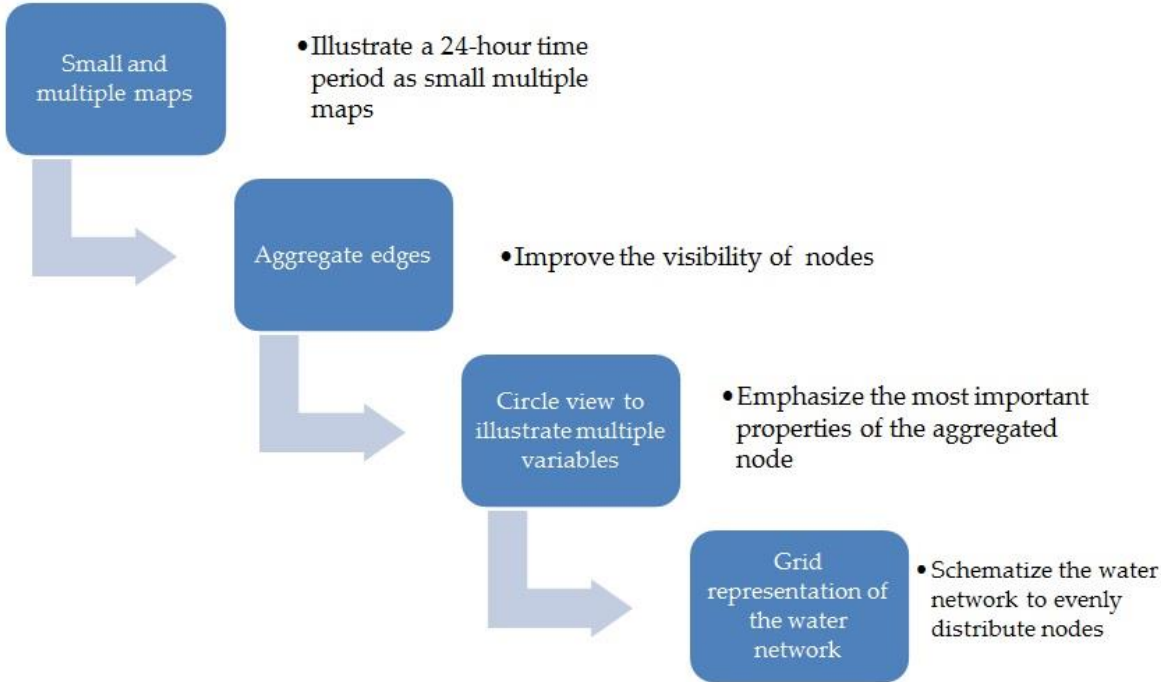
Figure 5.1 The visualization approach.

First, in order to obtain the nodal pressure and water age results over a 24-hour period of time throughout the network, an EPS feature of the U.S. Environmental Protection Agency EPANET software is used (Rossman 2000). Once EPANET simulations are completed (see Chapter 4, Section 4.1.2 EPANET simulation), results 24-hour time period of the hydraulic efficiency and water quality analysis are illustrated as small and multiple maps (see Figure 5.1). Then, small multiple maps require scaling down each map, which impacts the visibility of the nodes due to overlapping. Therefore, all the nodes along the edges are aggregated and represented as a single node. The circle view representation is used to visualize two values of a nodal pressure variable. Even though the points are simplified after aggregating the edges, the distances between the points can still be irregular. In other words, the network may have dense points at one region that may result in overlapping circles and loss of visibility. Therefore, the water network is mapped onto a grid, which allows a user to see every node individually without overlaps.

5.2   Small multiple maps

A standard way of displaying these time-varying performance measures for decision makers is the use of traditional animation techniques. The EPANET software allows users to display the result of EPS by animation technique. However, the problem with animation is that simultaneous and temporal changes may cause change blindness (Nowell et al. 2001). Representing each time step as small maps for time-oriented data may assist to overcome the problem of the animation. Decision makers can visually compare individual time steps (Tufte 2001, Tufte 1990).

In this dissertation, after the hydraulic simulation, in order to eliminate change blindness occurring during animation, using small multiple maps is proposed to visualize the result of hydraulic simulation (i.e. a 24-hour time period) on the WDSs. To be able to use small multiple maps to represent each time step, the wide extent of the WDS needs to be scaled down to fit into the smaller extents. This may result in loss of information due to overlapping nodes in some regions. Nevertheless, this representation will allow comparing each time step with the other time steps. In addition, the changes of each variable as well as relationships between the nodes will be visible to decision makers (Tufte 2001).

5.3   Aggregate edges

As mentioned before, due to the amount of time steps, each map has to be scaled down and to be fitted into one frame. In other words, using small multiple maps will require scaling each map down to fit in the extent. This results in deterioration of visibility due to the density of nodes since nodes will overlap on each map. In order

to overcome this problem, all the nodes along an edge (i.e., each pipe section) are aggregated into one single node and assigned to the end of that edge.

In this dissertation, an edge is a segment of a water network where two or more links are branching from the main pipeline. The aggregation process is started from the main water resource. All nodes until the first branching edge are stored at this point and a similar approach is followed throughout the network. Note that all edges are directed as water flows always in the same direction. Aggregating the edges and illustrating several nodes as one single node reduces the amount of point data and provides better visual results for decision makers. This aggregation method prevents overlapping node views and simplifies the network to give better visual overview in the WDS. Figure 5.2 illustrates the original network and after the aggregation of nodes. As can be seen in Figure 5.2-A, visibility of nodes is poor due to the overlapping in the original network. After the aggregation, each node can be seen individually (see Figure 5.2-B). However, all information of the aggregated group of nodes has to be shown. In addition, aggregation does not prevent overlaps where the nodes are densely located.

5.4 Multiple variables

Once all the nodes along the edges are aggregated and represented as a single node, it is necessary to illustrate multiple values of the variable at that node. Circle view (Keim et al. 2004) enables to illustrate multiple variables at one point. Circle view is based on dividing one circle into several sections and each section is symbolizing one variable. In addition, circles can be further divided into different rings to display a certain time interval. Using circle view to represent multiple values of one variable at one aggregated node of an edge emphasizes the most important properties of the node and enables perceiving the changes over time.

The nodal pressure and water age are main parameters to be visualized in this dissertation. As mentioned before, the nodal pressure parameter gives information about the water availability at a specific location. If the nodal pressure is under a certain level at one node, not enough water is supplied, which will severely affect the social satisfaction in the corresponding population (Tabesh and Dolatkhahi 2006). In addition, high nodal pressure will increase the cost of operation and maintenance as well as lead to water leakages from or bursts of the pipes.

Aggregating the nodes along the edges will cause loss of information about the pressure. However, decision makers need to identify whether or not the minimum and maximum nodal pressures are satisfied at each node. For this reason, two values of the nodal pressure variable (i.e. "the number of times nodal pressure is satisfied" and "the number of times nodal pressure is not satisfied") are represented in a circle view at each node.
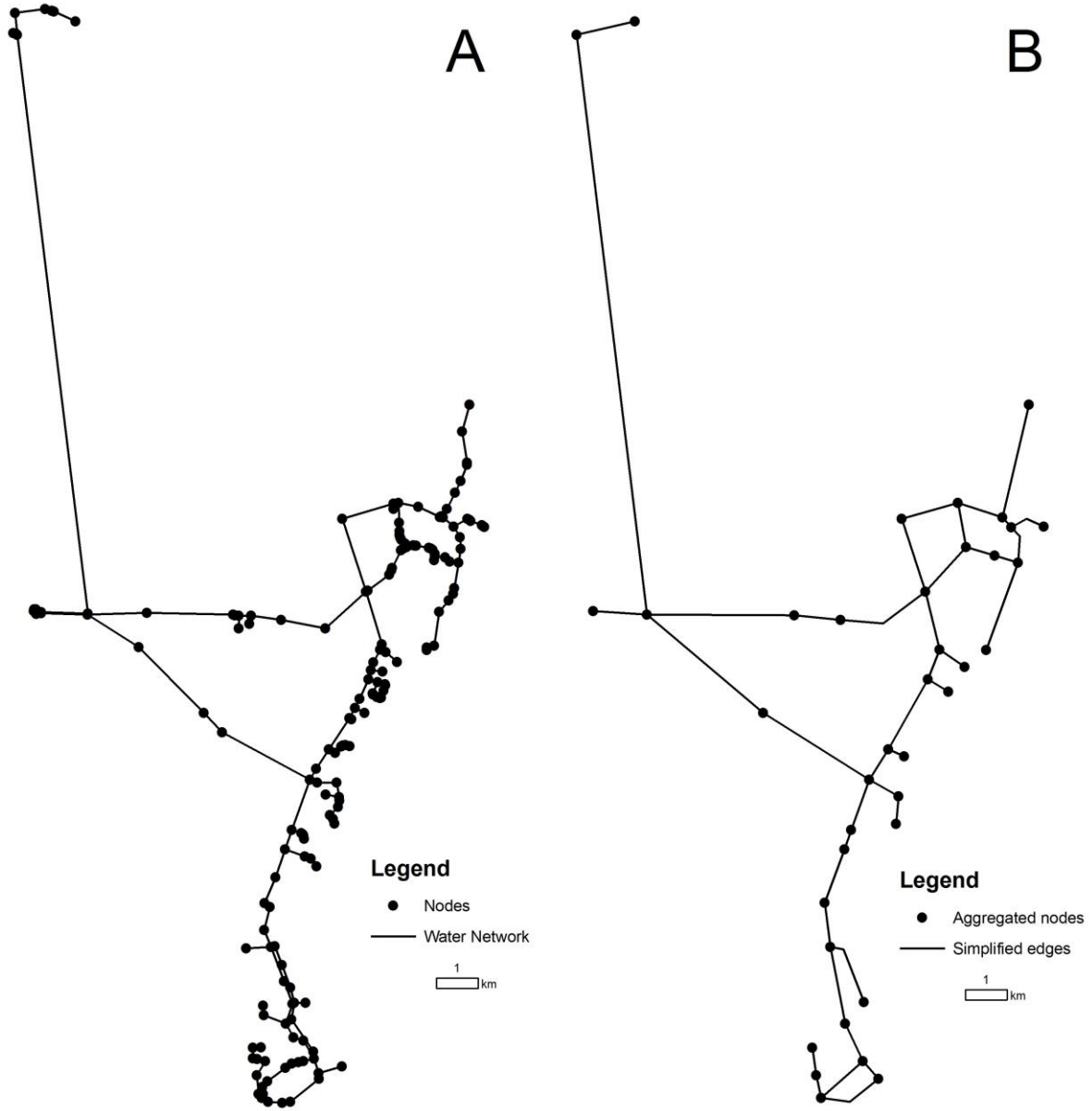
Figure 5.2 A. Original network. B. Aggregated edges.

The ideal pressure range for the technical sustainability evaluation is explained in detail in Chapter 4, Section 4.1.3. In order to illustrate the nodal pressure performance using circle views, the following function is used.

$$P_{j,t} = \begin{cases} unsatisfactory\ (0) & P_{j,t} < P_{min} \quad \vee \quad P_{j,t} > P_{max} \\ satisfactory\ (1) & P_{j,t} \geq P_{min} \quad \wedge \quad P_{j,t} \leq P_{max} \end{cases} \tag{5.1}$$

$$N_{i,0} = \#\ of\ times\ P_{j,t} = 0 \tag{5.2}$$

$$N_{i,1} = \# \ of \ times \ P_{j,t} = 1 \tag{5.3}$$

where $P_{j,t}$ is the pressure at node j at time t; P_{min} is the minimum pressure (i.e., 40 psi); and P_{max} is the maximum pressure (i.e. 80 psi). N_i represents the nodes that are aggregated along the edges. $N_{i,1}$ is the total number of satisfactory pressure conditions at aggregated edge i while $N_{i,0}$ is the total number of unsatisfactory nodal pressures at aggregated edge i.

The mapping of these two values to the circle view is shown in Figure 5.3. In the circle view representation, the inner ring is the current time step while the outer ring corresponds to the next time step. Blue segments represent the amount of satisfactory events (i.e. the number of times nodal pressures or water ages are in the satisfactory state), while yellow segments represent the amount of unsatisfactory events (i.e. the number of times nodal pressures or water ages are in the satisfactory state the number of times nodal pressures are in the satisfactory state). Thus, decision makers can visually see how a system responds or how fast the network recovers from a failure. Further, they can compare the current time step with the next time step. Therefore, immediate changes at the next time step can be detected examined in detail if necessary.

The overall water quality of an urban water supply is assessed using the water age parameter (i.e. the detention time) in water distribution networks (Rossman 2000). Detention time specifications are site-specific and changes based on water quality requirements, fire flow requirements etc. (EPA 2002).

Time step 100-101

Time Step 100 (inner ring):
¾ Unsatisfactory
¼ Satisfactory

Time Step 101 (outer ring):
½ Unsatisfactory
½ Satisfactory

Figure 5.3 Multiple values of a nodal pressure variable are represented as circle view, which was first proposed by Keim et al. (2004).

The ideal water age range for the technical sustainability evaluation is explained in detail in Chapter 4, Section 4.1.3. In order to determine the pressure performance, the following function is used. In order to illustrate the water age performance using circle views, the following function is used.

$$WA_{j,t} = \begin{cases} unsatisfactory\ (0) & WA_{j,t} > WA_{max} \\ satisfactory\ (1) & WA_{j,t} \leq WA_{max} \end{cases} \tag{5.4}$$

$$N_{i,0} = \#\ of\ times\ WA_{j,t} = 0 \tag{5.5}$$

$$N_{i,1} = \#\ of\ times\ WA_{j,t} = 1 \tag{5.6}$$

where $WA_{j,t}$ is the water age at node j at time t; WA_{max} is the upper limit for water age parameter (i.e. 24 hour). N_i represents the nodes that are aggregated along the edges. $N_{i,1}$ is the total number of satisfactory water age performance at aggregated edge i while $N_{i,0}$ is the total number of unsatisfactory water age performance at aggregated edge i.

Sustainability of the water resources is explained in the concept of resiliency, reliability and vulnerability performance criteria by Sandoval-Solis (2011). The fast recovery of the nodes (instant transaction from yellow to blue) gives information about how fast the system recovers from a failure explained as resiliency in Hashimoto et al. (1982). Reliability is defined as how often the system is in a satisfactory state. Vulnerability is the extent or duration of unsatisfactory conditions (Hashimoto et al. 1982). The resiliency concept can be understood as the duration of yellow on the nodes. Reliability is the frequency of the blue circle view and vulnerability is the frequency and duration of the yellow view on the WDS. Figure 5.4 gives circle view representations of these performance criteria. Depending on the size and density of circle views, illustrating more than two values of a variable can be difficult to be identified by decision makers.

Figure 5.4 A. Reliability example. B. Vulnerability example. C. Resiliency example.

5.5 Grid representation of the water network

In the water distribution network, nodes (i.e. water consumption points) are unevenly distributed. While some regions are dense, others are sparse. In order to avoid overlaps, the representation of the WDS needs to be modified retaining the topology of the network. This kind of modification has been used in transportation to create metro maps, which are simplified versions of the complex infrastructure network, therefore, easier for users to read.

Henry Beck produced one of the first schematic maps in 1933 using simple rules such as horizontals, verticals, and diagonals lines (Garland 1994). Bartram (1980) proved the effectiveness of schematic public transport maps. Dinkla et al. (2012) proposed compressed adjacency matrices to visualize gene regulator networks. In their study, node-link diagrams and standard adjacency matrices are rearranged in order to obtain a compact visualization of a network. In addition, Tufte (1997) describes automatically produced metro maps. In the water resources field, skeletonization of water networks (using the part of the network that has significant impact on the overall hydraulic behaviors) is utilized for hydraulic simulation purposes. However, schematizing water networks is not a common approach for visual purposes. On the other hand, it would substantially improve the decision-making process.

In order to prevent overlapping nodes, the water network is repositioned on a grid, which allows a user to see every node individually. The study area is divided into 500 m by 500 m grid points. In order to assign the locations on the grid, the nearest distances from the grid to the network nodes are calculated. Then, the new node location is assigned to the closest grid point. If more than one node is near the same grid point, the closest one is assigned to that particular grid point and the second node will be shifted to the second nearest grid point. Once the new locations of the nodes are assigned, nodes are connected to each other using the Bresenham line algorithm (Bresenham 1965).

The main advantage of using a grid layout is that the topology of the network is preserved. Users or decision makers are able to see the overall network and read each node individually without any overlapping problems. The size of the circle view and the grid distance are arranged such that even if the nodes are located next to each other, the connections (i.e., pipes) are still visible. Thus, this representation provides a clear image of the urban WDS to decision makers. Figure 5.5 illustrates the modifications on the network.

As mentioned before, schematizing the water distribution network provides even distribution of network demand points (i.e. nodes). Even though aggregating nodes significantly simplifies the network, once circle view approach is applied to the network, there were still overlaps at some locations. By schematizing the network and distributing nodes evenly on the study area, overlaps due to circle view application are avoided.
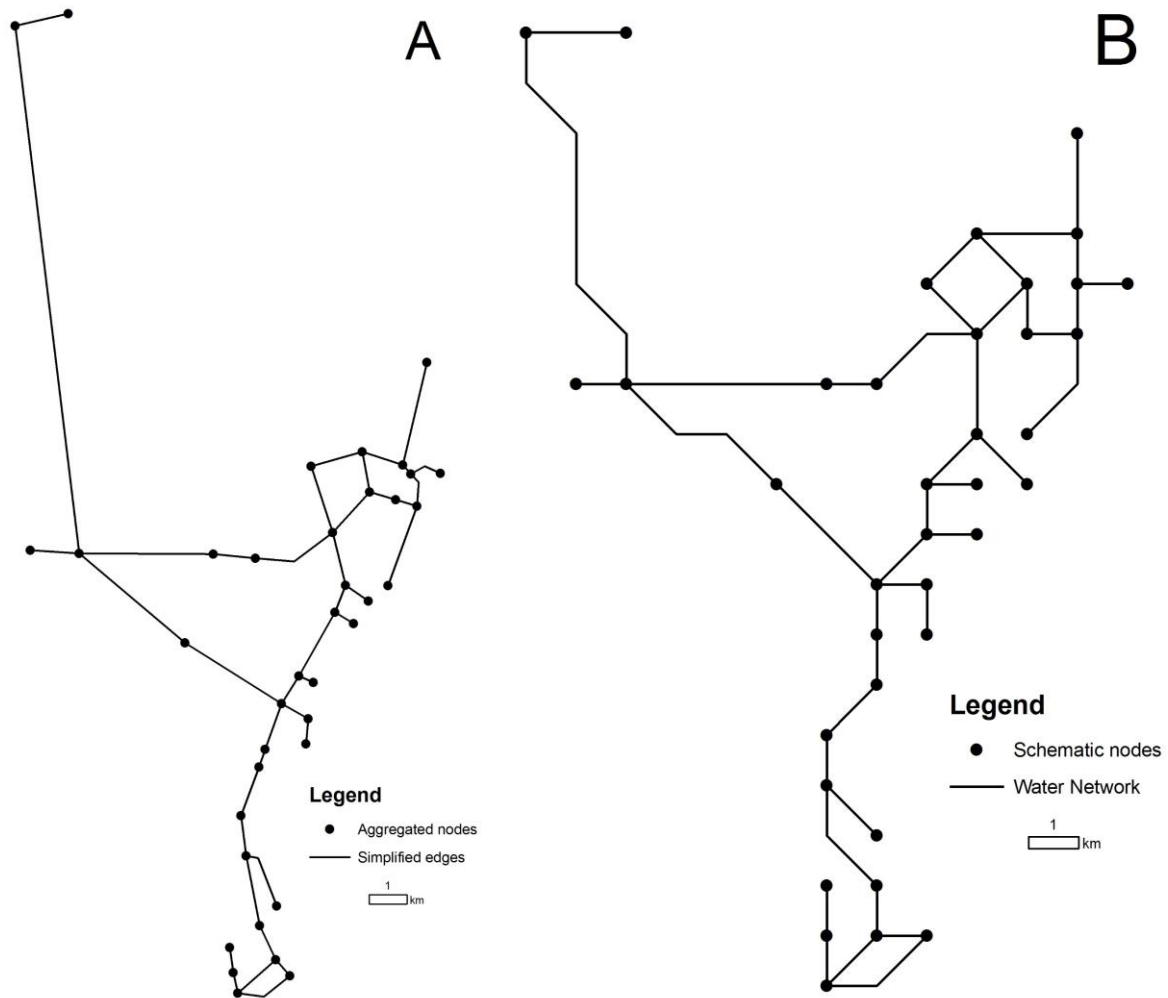
Figure 5.5 A. Aggregated nodes. B. Schematized network with new node locations.

5.5.1 Bresenham line algorithm

Bresenham's algorithm which is proposed by Bresenham (1965) is an effective implementation to plot straight and quadric line segments in a two-dimensional space. It is fast as well as easy to implement and widely used in computer graphics. The main aim of the algorithm is to depict a line segment between two coordinates on a grid (Rashid et al. 2013). First, x coordinates are determined step by step from initial point to the next point (from x_i to x_{i+1}). Then, the closest y coordinates are selected (from y_i to y_{i+1}). In order to choose y-coordinate, a decision parameter p_k is required. The algorithm is given below:

(x_0, y_0) are the starting points of the line segment and (x_e, y_e) are the end points of the line segment.

First, calculate the constant

$\Delta x = x_e - x_0$

$\Delta y = y_e - y_0$

Calculate the first value of the decision parameter p_0;

$$p_0 = 2\Delta y - \Delta x$$

For each value of x_i on the line segment, if $p_i < 0$, then the next point to plot is (x_{i+1}, y_i) and:

$$p_{i+1} = p_i + 2\Delta y$$

Otherwise, the next point to plot is (x_{i+1}, y_{i+1}) and:

$$p_{i+1} = p_i + 2\Delta y - 2\Delta x$$

Continue until x_e, y_e is reached.

5.6   Interactive tool design

An interactive tool, designed in this dissertation, is implemented by Alina Freund (Freund et al. 2014) using Java by utilizing the GUI library JavaFX which is compatible in cross-platform and web-interface. The interactive tool window is given in Figure 5.6.
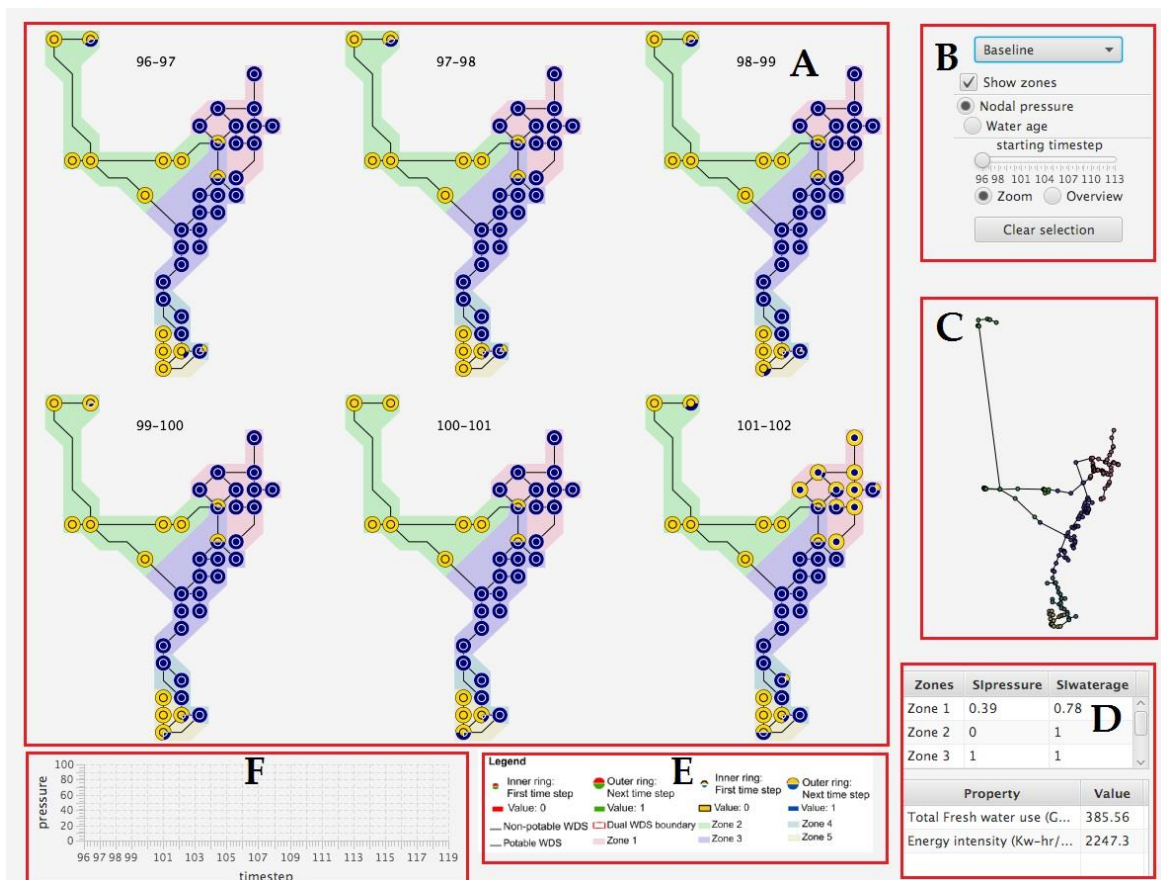
Figure 5.6 Urban water system planning tool. A. The main data frame. B. Interaction tools C: the secondary data frame. D. Tables for scenarios. E. Legend. F. Graph tool.

The tool is incorporated in the newest Java distribution by the Oracle Company and can be run on different devices. JavaFX is flexible to designing high-responsive UIs. In order to load the shapefiles that are created for each current population and water demand scenario, geotools library is used for processing the geospatial data. The Java code for programming the interactive tool is given in Appendix 2.

The interactive tool window contains multiple data frames. One data frame for the proposed visualization approach, and the other one is to visualize the original data. In addition to the geospatial data, there are tables which give information about the selected scenario, a graph option which illustrates either nodal pressure or water age parameters over a 24-hour period of time, and a legend.

The urban water system planning tool uses shapefiles including, the zone boundary, original network data (i.e. nodes and pipes), nodes for circle view representation, and edges for the grid representation of the network. Table 5.1 provides information about the data that is used to create the urban water system planning tool. Nodes for the original water network and for circle view data layers are created for each scenario of each parameter. For example, for the Scenario I: baseline scenario, there are two separate data layers for the nodal pressure and water age.

Table 5.1 Data types and database for the urban water system planning tool.

Shapefile	Vector data type	Database
Zone boundary	Polygon	Names of the zones
Nodes for the original water network	Point	The EPS results for the nodal pressures and water ages
Pipes for the original water network	Polyline	-
Nodes for circle view	Point	Total number of unsatisfactory water age/nodal pressure performance Total number of satisfactory water age/nodal pressure performance
Edges for the grid representation of the network	Polyline	-

There are six time steps available at a time for the circle view representation (see Figure 5.6-A. There is a time slider option which enables decision makers and/or experts to manually change the time steps (see Figure 5.6-B). Zones presented on the main data frame are color coded with de-saturated colors in order to avoid the distraction and emphasize the circle view representation (Ware 2004). The secondary

data frame represents the original WDS (see Figure 5.6-C). For the reclaimed water for non-potable water demand and fire flow scenarios, an inset is added to each of the multiple maps and to the original water network frame. In order to differentiate the potable and non-potable WDSs, a separate color-code is used for the circle views in the reclaimed water for non-potable water demand and fire flow scenarios. The color code representations are given in legend (see Figure 5.6-E).

In addition, tables, provided in the urban water system planning tool, display the sustainability indices as well as total base demand, total freshwater use, energy intensity and the options for water demand variations for the reclaimed water for non-potable water demand and fire flow scenarios (see Figure 5.6-D). These tables are updated whenever a user selects a scenario. A graph tool given in Figure 5.6-F provides time series graph for a selected parameter of a selected circle view (i.e. nodal pressure or water age).

Figure 5.6-B illustrates the interaction tools. For example, using the combo box at the top of the tool, decision makers and/or experts are able to choose the scenario to display in the main data frame. Selecting a scenario updates the tables and provides detail information about the selected scenario. "Show zone" tool provides an option to decision makers and/or experts to remove the zone boundaries.

Radio buttons allows switching between the nodal pressure and water age parameters. Decision makers and/or experts can select a starting time step in order to explore the data set and observe the changes through the simulation time. There are two options to display the original data set at the secondary data frame. The "zoom" radio button enables to display the original nodes for a selected circle view in a smaller scale and to highlight the edge where nodes are located on. The "overview" radio button highlights the location of the selected circle view on the original data frame. The difference between the "zoom" and "overview" is that the "zoom" button illustrates the original nodes that the selected circle view represents in a larger scale. But the "overview" button keeps the original data overview and highlights edges that the selected circle view represents. The highlighted edges and nodes can be cleared via button click.

5.7 Conclusion

In this chapter, a new visualization approach for a schematic representation of the water network is presented using the circle view approach for multiple time dependent variables. Combing small multiples, aggregated edges, circle views, and a grid layout increased the readability of the visualization over existing techniques using geographical layouts and animation. This method is further improved for the current population and water demand scenarios by creating an interactive tool. Urban water system planning tool facilitates the scenario evaluation and enables communicating with the data.

CHAPTER 6

SCENARIO EVALUATION

6.1 Scenario I: baseline

In order to evaluate the technical and environmental sustainability of the WDS in the baseline scenario, an EPS is applied using the EPANET software. The results of the EPS for the nodal pressure and water age parameters from time step 96 to 108 and from 108 to 119 are illustrated using the proposed visualization approach and given in Figures 6.1 and 6.2, respectively. As can be seen from these figures, the center of the water distribution network which is corresponding to Zone 3 is the most reliable part of the network in terms of nodal pressure parameter. Since the nodal pressure at this part of the network is continuously in the identified satisfactory nodal pressure range (i.e. between 40 psi and 80 psi). The identified satisfactory nodal pressure range is represented as "blue" in circle views.

On the other hand, the south of the network where Zone 5 is located is continuously in the vulnerability state. This means that the nodal pressures of the nodes at this location are either less than 40 psi or higher than 80 psi. The circle views (i.e. group of nodes along the edges) at this location are represented as "yellow". One reason for the vulnerability at this location is that Zone 5 is at the most distant location from the main resource. Another reason is that the elevation changes significantly from Zone 4 to 5, making it difficult to sustain nodal pressures in this portion of the water network. Consequently, high vulnerability and low resiliency and reliability indices at this location result in the low $SI_{overall}$ scores. In these figures, the significant change starts from the time step 102 which corresponds to the peak demand hour. The water age parameter in the baseline scenario is visualized separately. Figures 6.3 and 6.4 represent the changes during the simulation time in the WDS.
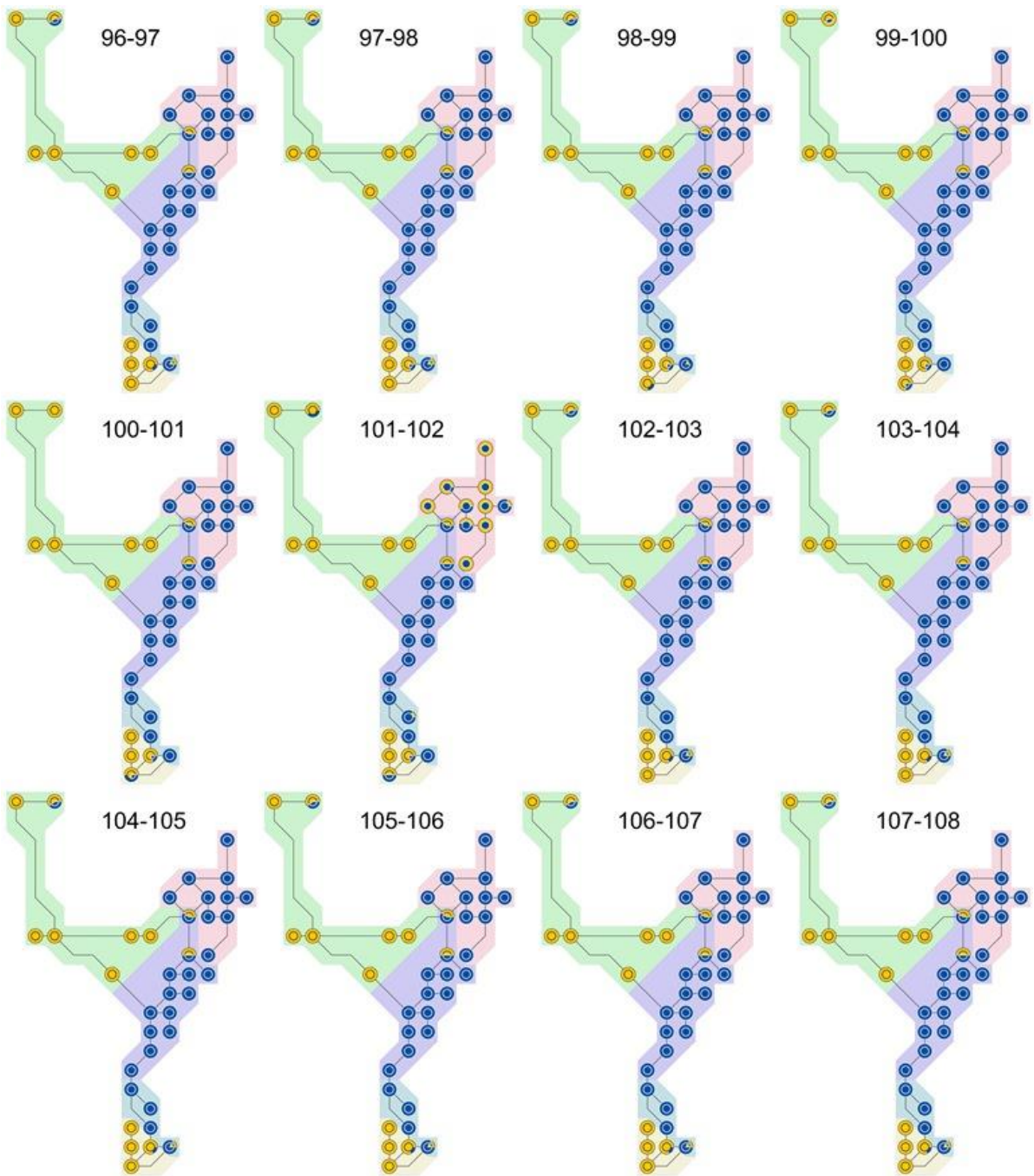
Figure 6.1 The EPS results for nodal pressure values in the baseline scenario from hour 96 to 108.
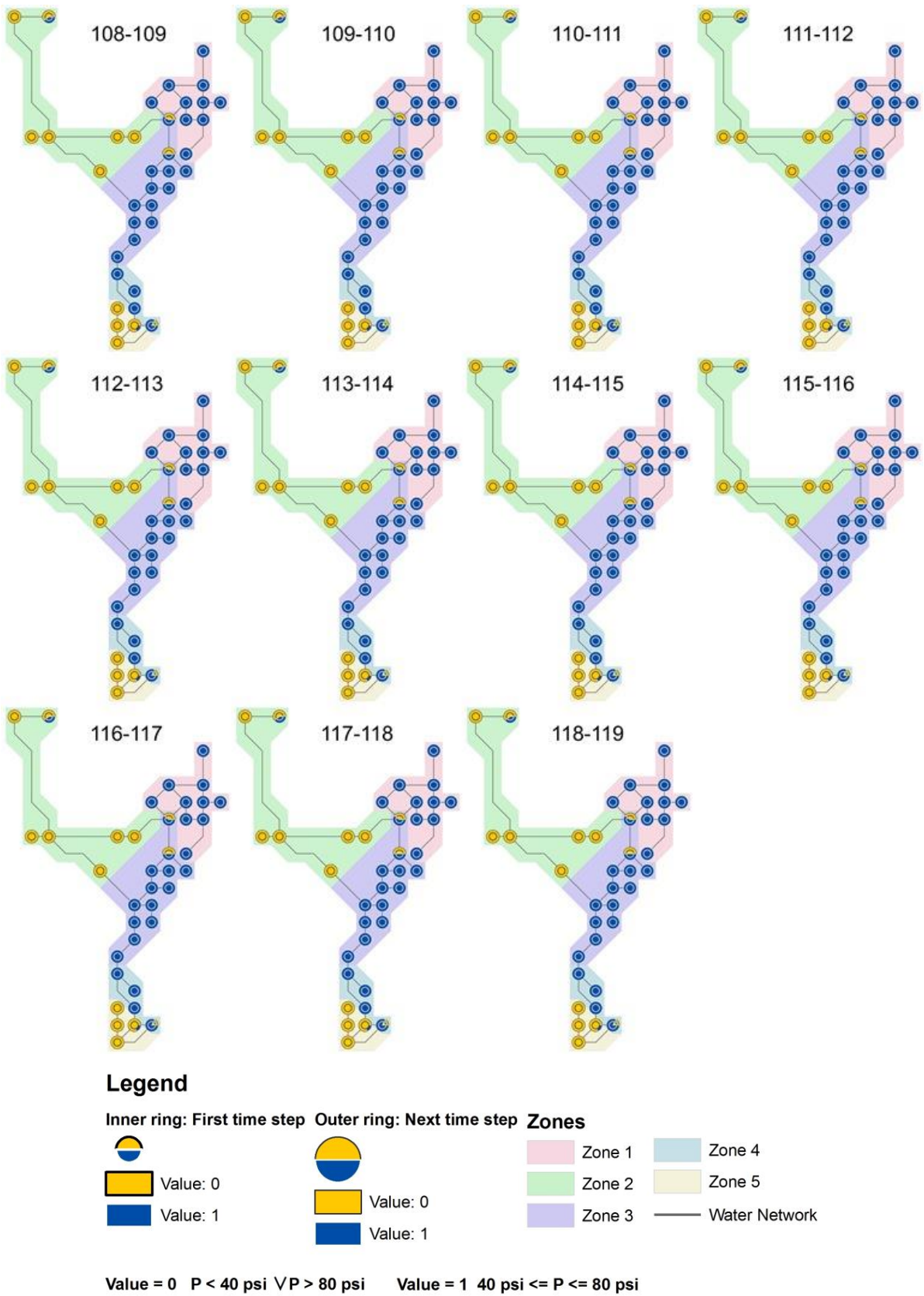
Figure 6.2 The EPS results for nodal pressure values in the baseline scenario from hour 108 to 119.
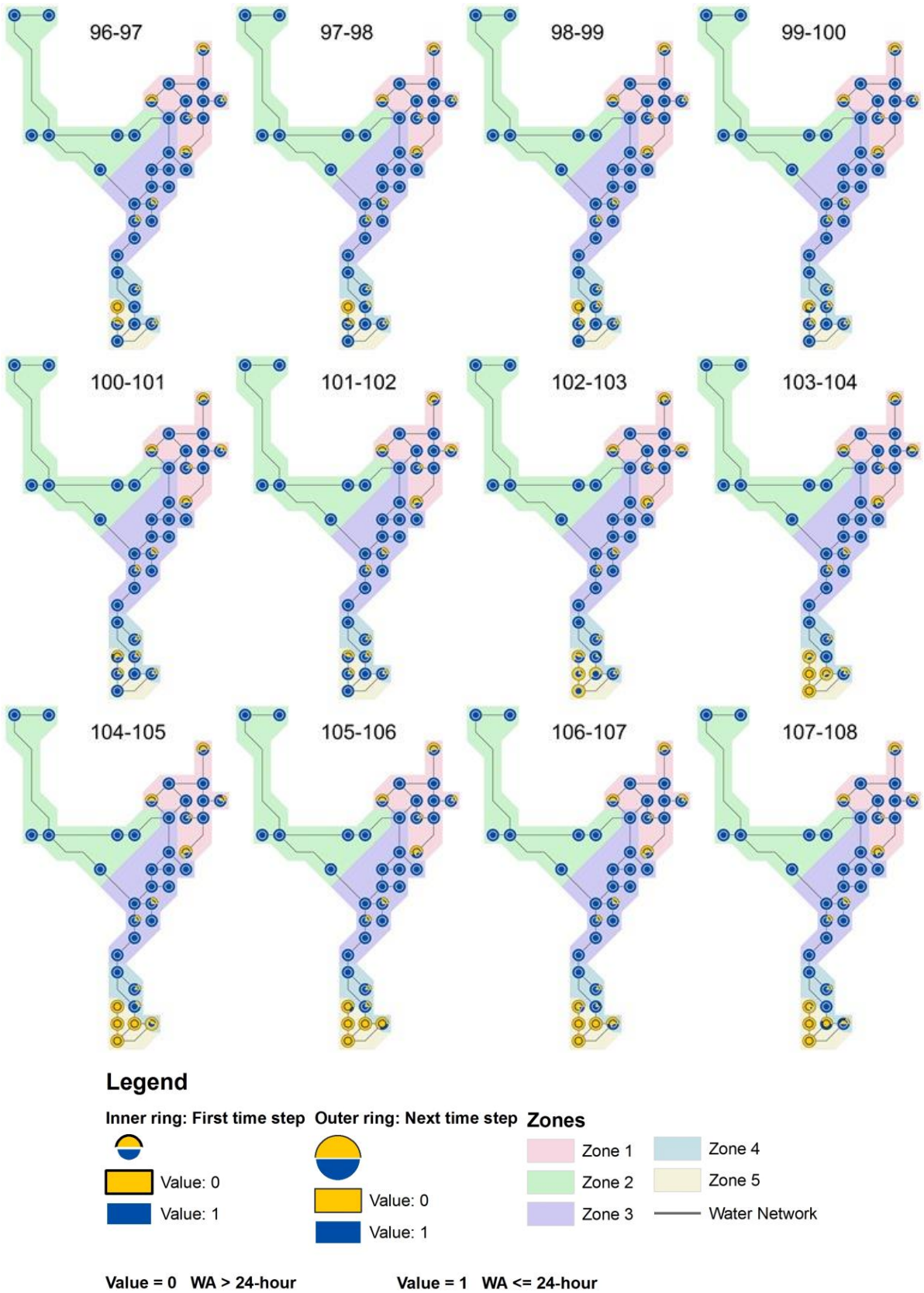
Figure 6.3 The EPS results for water age values in the baseline scenario from hour 96 to 108.
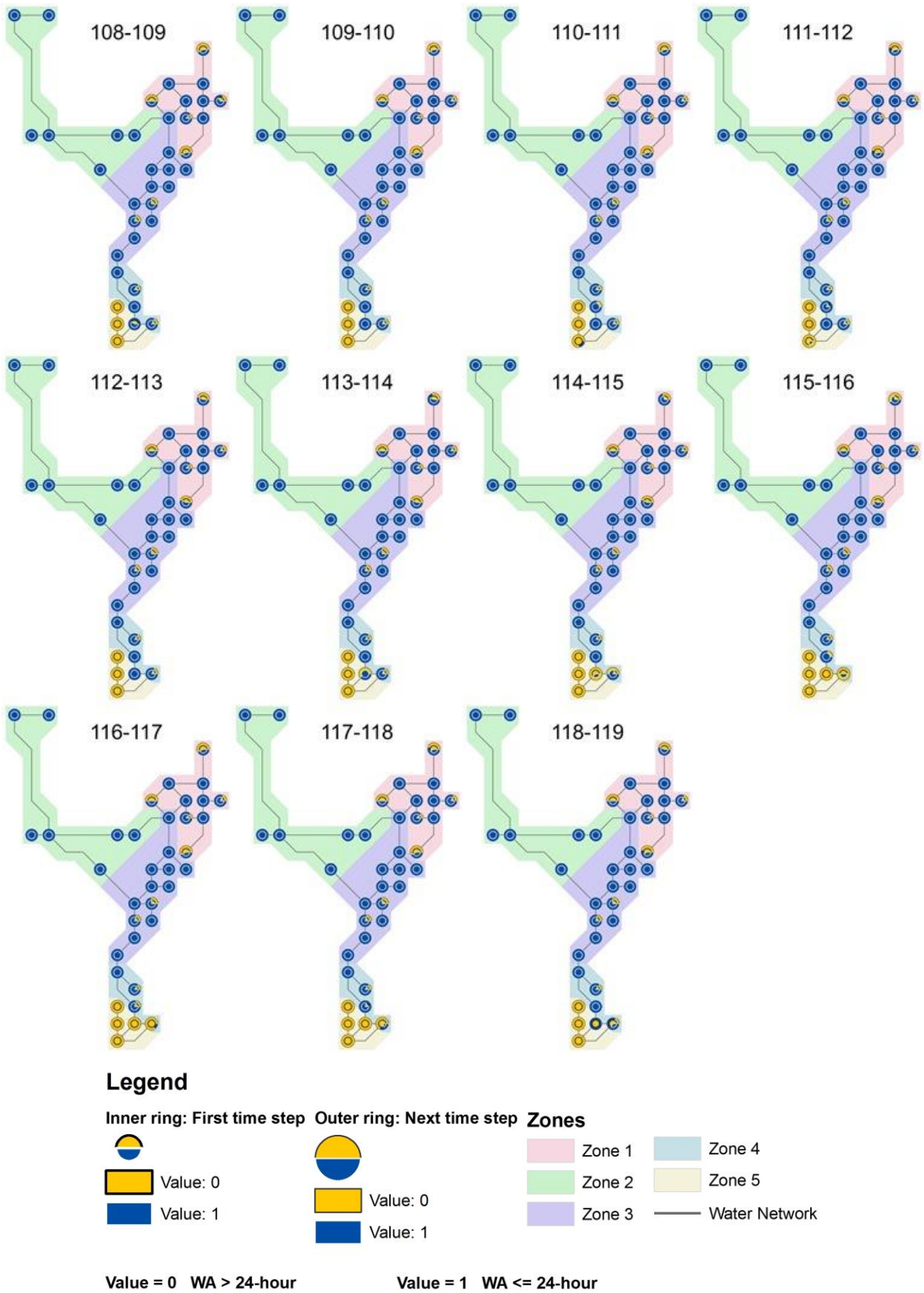
Figure 6.4 The EPS results for water age values in the baseline scenario from hour 108 to 119.

Even though, visualization results for the nodal pressure and water age parameters demonstrate reliability, vulnerability and resiliency performance criteria, in order to evaluate the sustainability of the water distribution network, these performance criteria have to be evaluated for each node individually and then aggregated into an overall sustainability for each zone. For this purpose, the EPS results (i.e. from hours 96 to 119) are exported into Excel spread sheets in order to calculate the technical sustainability of the water network. The reliability, resiliency and vulnerability performance criteria are calculated using equations 4.3, 4.4, and 4.5, respectively and the details of definitions are explained in Chapter 4, Sections 4.1.4, 4.1.5 and 4.1.6. For example, Figure 6.5 is the nodal pressure performance of the node number 117 at zone 2. In Figure 6.5, red lines represent upper and lower limits (i.e. upper and lower thresholds for nodal pressure is from 40 psi to 80 psi). For the node 117, the total number of times the node is in the satisfactory state is 8 while the total number of time the nodal pressure at node 117 is in the unsatisfactory state is 16. Therefore, using the equation 4.3, reliability performance of node 117 is approximately 0.3. Vulnerability and resiliency performances of node 117 are calculated in the same method using equations 4.4 and 4.5. Table 6.1 lists the performance criteria together with the SI in terms of the nodal pressure for the node 117.

Table 6.1 Performance criteria and SI for node 117.

Performance criteria	Node 117
Reliability (REL)	0.33
Resiliency (RES)	0.31
Vulnerability (VUL)	0.48
SI$_{pressure}$	0.38
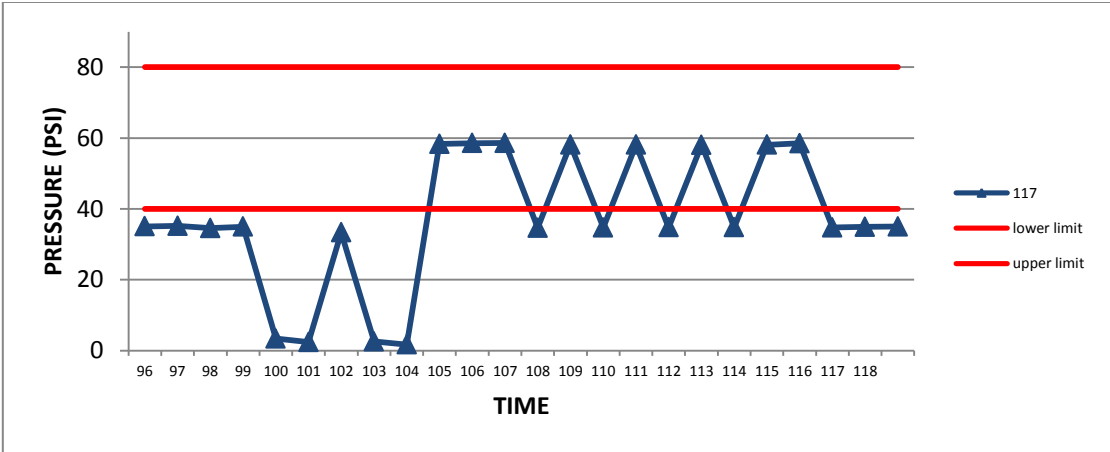
Figure 6.5 Pressure performance of node 117 in Zone 2.

Figure 6.6-A and B illustrate the sustainability indices of nodal pressure and water age at each node for Scenario I: baseline, respectively. In these figures, sustainability indices of each node are represented in four categories. The SI values in between 0 and 0.25 are representing the unacceptable state and marked as red. The SI in the ideal state (i.e. from 0.75 to 1) is marked as blue. In the following step, the SI is calculated for each zone by weighting sustainability scores of each node by its corresponding demand using equation 4.7. Demands at each node are used as a weighting factor for each node. Once sustainability indices for each zone are calculated for the nodal pressure and water age, these values are aggregated into a $SI_{overall}$ using equation 4.8 as explained in the methodology chapter.

Table 6.2 gives the overall SI (i.e. $SI_{overall}$) of each zone together with the sustainability indices for the nodal pressure and water age. Results of the $SI_{overall}$ calculation show that among all zones, Zone 5 has the lowest sustainability score since an SI value in between 0 and 0.25 is identified as "unacceptable" state in terms of the sustainability of the WDS. As mentioned before, reasons such as being located at the most distant location from the main reservoir and the significant elevation changes from Zone 4 to 5 are challenging to sustain nodal pressures at this portion of the water distribution network.
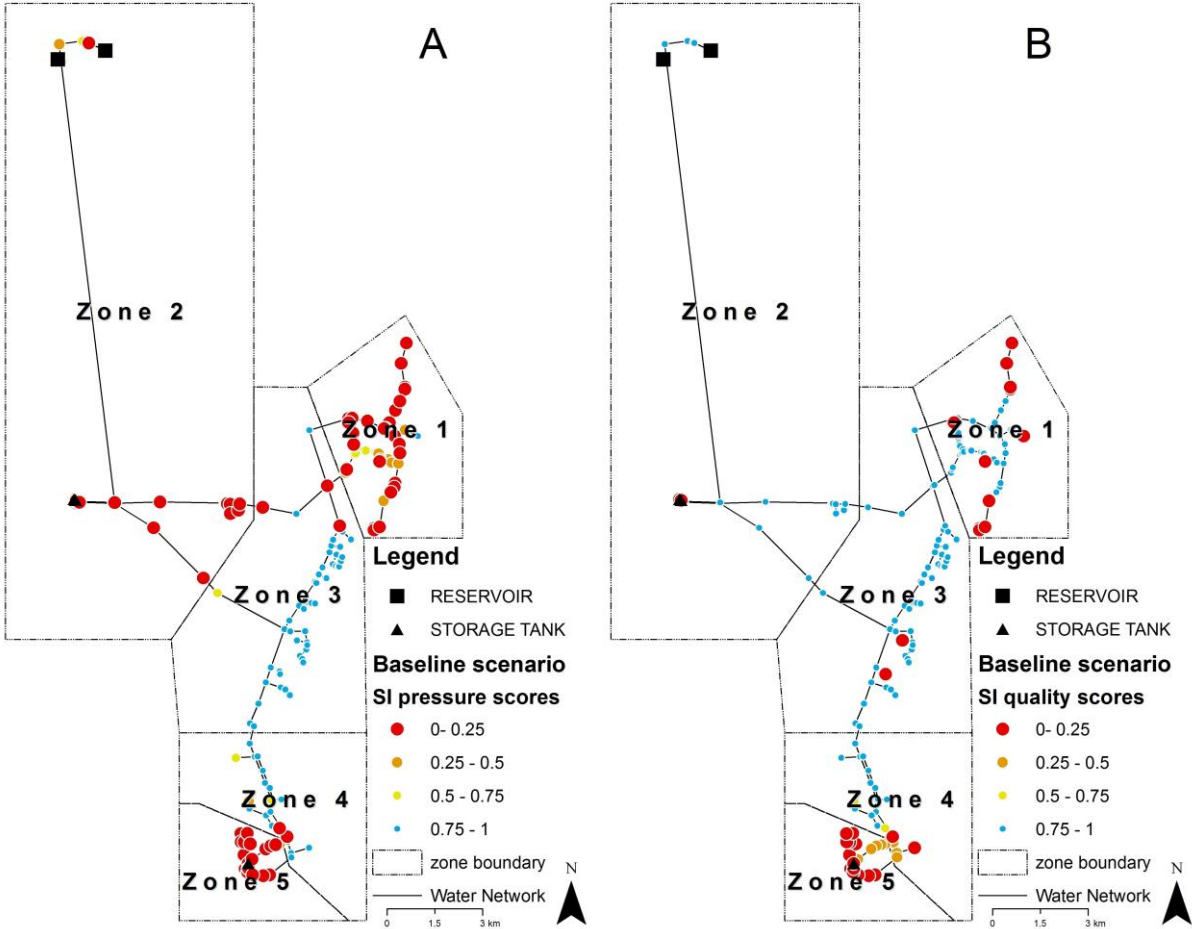
Figure 6.6. A. $SI_{pressure}$ for baseline scenario. B. $SI_{waterage}$ for baseline scenario.

Table 6.2 SI scores of each zone in Scenario I: baseline.

Zones	$SI_{pressure}$	$SI_{waterage}$	$SI_{overall}$
Zone 1	0.39	0.78	0.59
Zone 2	0	1	0.50
Zone 3	1	1	1
Zone 4	0.89	0.92	0.91
Zone 5	0.03	0.10	0.07

6.2   Scenario II: new pump

In the baseline scenario, the problematic location (i.e. zone with the unacceptable $SI_{overall}$ score) is identified as Zone 5. In order to improve the sustainability of the WDS, a more traditional approach is proposed as an alternative solution in the new pump scenario. For this purpose, the potable WDS is preserved and new network components are added into the network in order to increase the technical sustainability and to evaluate the environmental sustainability of the centralized WDS when there is a fire flow in the water network. Additional network components such as booster pumps, elevated storage tanks to serve during the fire flow are proposed as a solution to the problem of the low $SI_{overall}$ at Zone 5. Therefore, a booster pump to be located in close proximity of Zone 5 is proposed to increase nodal pressures and decrease water ages in the water distribution network. Another booster pump is added to the same location to serve only during the fire flow. The network modifications for the "new pump" scenario are shown in Figure 6.7.

6.2.1   The technical sustainability calculation of the new pump scenario

The EPS is applied to the new pump scenario and results of the simulation from time step 96 to 119 are visualized using the proposed visualization methodology. Note that, fire flow requirements have not been applied to this EPS yet but will be simulated at the next section. Figure 6.8 demonstrates the EPS results for the nodal pressure from time step 101 to 105. The peak demand is corresponding to time steps 102, 103, and 104. Since the most significant changes occur in this period, only these steps are represented in this figure. As can be seen in this Figure 6.8, the nodal pressure performance of the water distribution network has improved significantly. Nodes corresponding to Zone 5 were in the vulnerability state in the baseline scenario which is eliminated considerably in the new pump scenario. Similarly, the nodal pressure performance of nodes located at Zone 1 has improved significantly comparing to the baseline scenario.
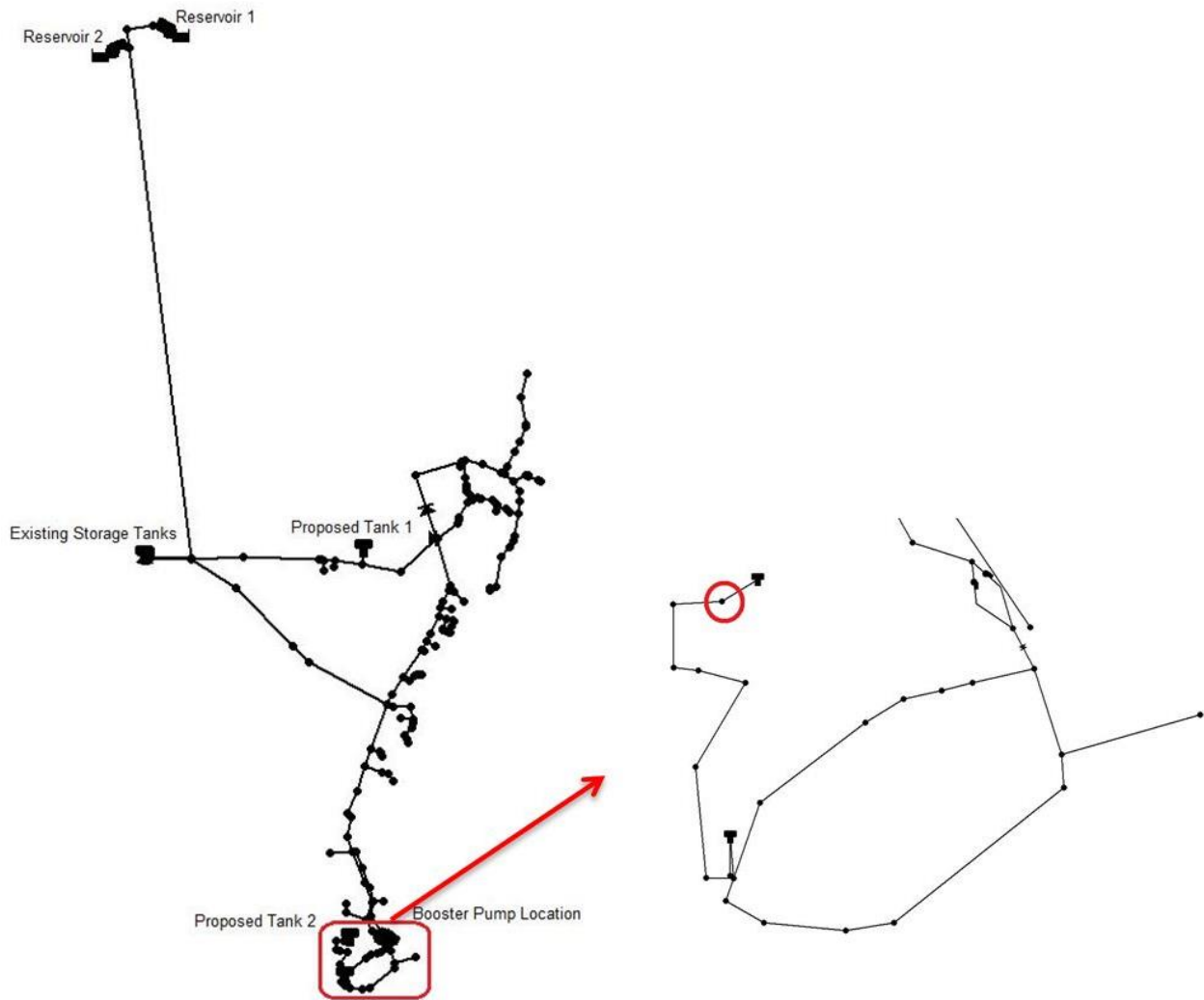
Figure 6.7 Network modifications and the simulated fire flow location.

The proposed visualization approach is applied to the water age parameter and results of the EPS for the new pump scenario are represented in Figure 6.9. The nodes located at Zone 5 in a continuous reliability state (i.e. represented as blue) indicate that the proposed network modifications assist to improve the water age scores at this part of the WDS.

The next step is to calculate reliability, resiliency and vulnerability performance criteria numerically and then assess technical sustainability of the new pump scenario. The reliability, resiliency and vulnerability performance criteria are calculated using equations 4.3, 4.4, and 4.5, respectively. The detailed example of how to calculate performance indices has been explained previously.
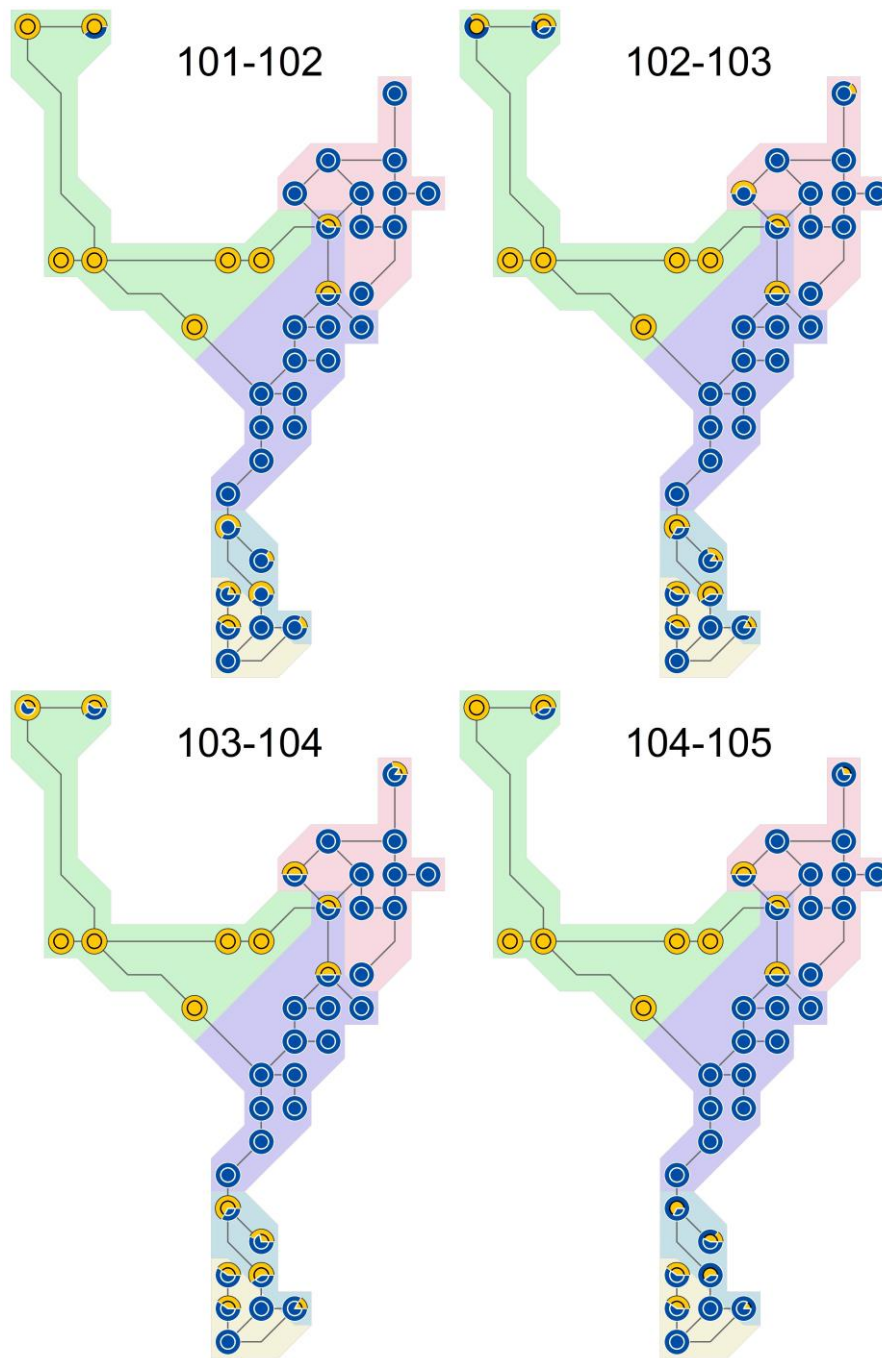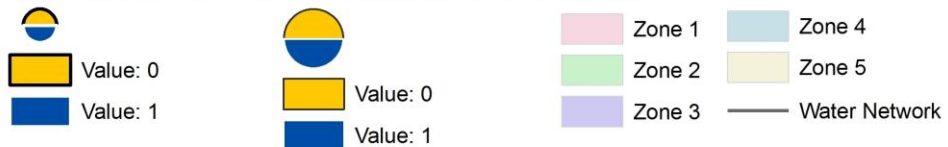
Figure 6.8 The EPS results for the nodal pressure parameter from time step 101 to 105.
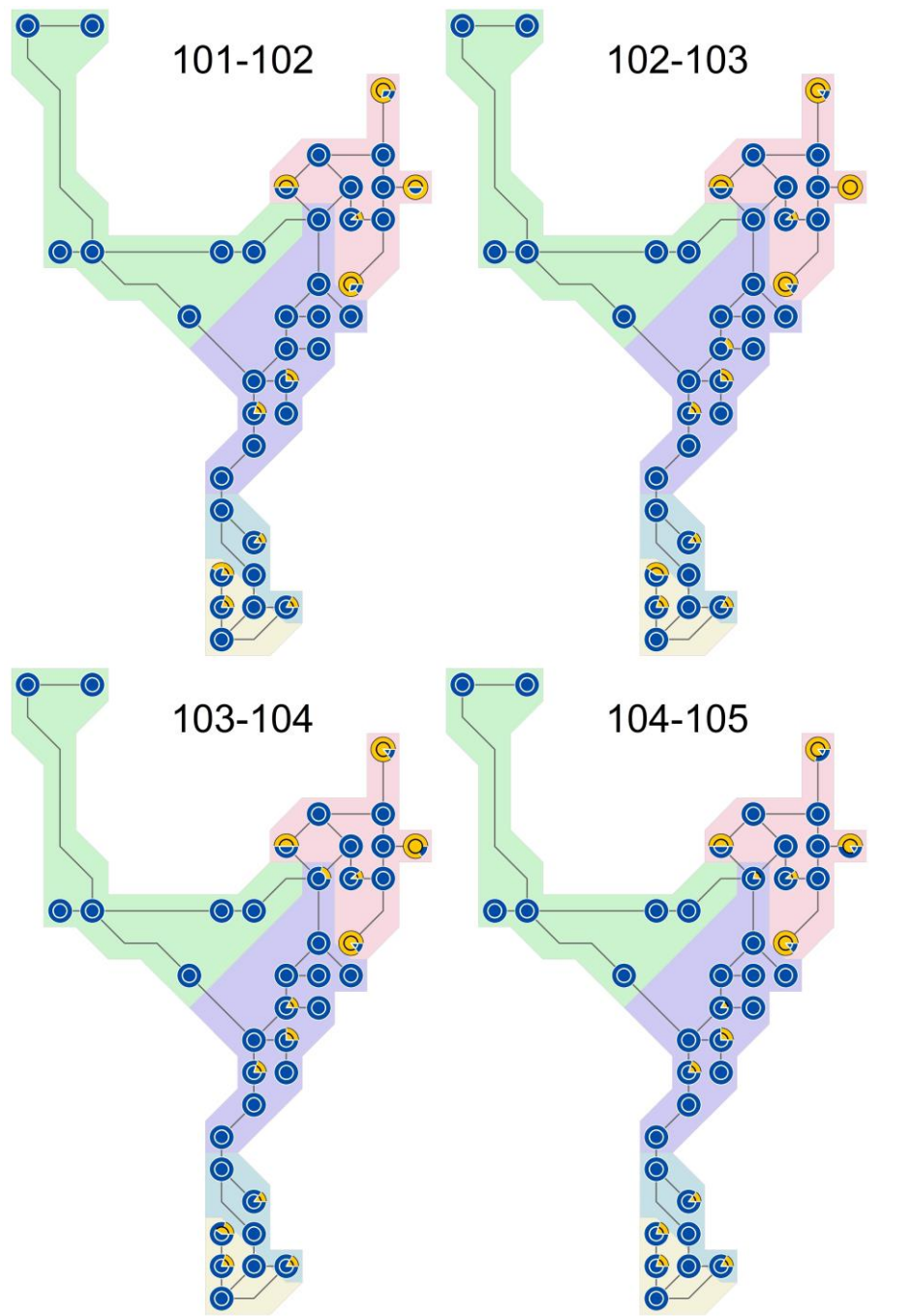
Figure 6.9 The EPS results for the water age parameter from time step 101 to 105.

Table 6.3 demonstrates the result of the technical sustainability calculations for the nodal pressure and water age parameters (i.e. $SI_{network,pressure}$ and $SI_{network,waterage}$ respectively), in addition $SI_{pressure}$ and $SI_{waterage}$ scores for each zone are presented in this table. As can be seen from table 6.3, $SI_{pressure}$ and $SI_{waterage}$ have improved significantly comparing to the baseline scenario. The $SI_{pressure}$ score of Zone 5 has increased from 0.03 to 0.66 and the $SI_{waterage}$ value has increased from 0.21 to 0.96. In addition, the technical sustainability of the WDS for the nodal pressure (i.e. $SI_{network,pressure}$) and water age (i.e. $SI_{network,waterage}$) values are 0.54 and 0.93, respectively.

Table 6.3 The technical sustainability results for Scenario II: new pump.

Technical sustainability	$SI_{network,pressure}$	0.54	**Zones**	**$SI_{pressure}$**
			Zone 1	0.53
			Zone 2	0
			Zone 3	0.97
			Zone 4	0.56
			Zone 5	0.66
	$SI_{network,waterage}$	0.93	**Zones**	**$SI_{waterage}$**
			Zone 1	0.71
			Zone 2	1
			Zone 3	1
			Zone 4	0.99
			Zone 5	0.96

6.2.2 The environmental sustainability of the new pump scenario

In the new pump scenario, the current population and the water demand have not changed but alternative solutions to the current potable water distribution network problems have been proposed. Since the population and the water demand are not modified in this scenario, overall base demands (i.e. total fresh water use) have not altered as well. The total fresh water use is approximately 385 GPM in the WDS. However, new booster pumps are added into the water distribution network which has an effect on the energy intensity criteria. The energy intensity of the baseline scenario was approximately 2247 Kw-hr/Mgal and in the new pump scenario without fire flow condition, it is circa 2429 Kw-hr/Mgal. Although an increase in the energy intensity criterion is expected, there is only 8 % increase of the energy intensity criteria in the new pump scenario. In the baseline scenario, there are two pumps located in the close proximity of main reservoirs. In the new pump scenario, the percentage utilizations of pump 1 and pump 2 have decreased approximately 12 % and 19 %, respectively. Table 6.4 demonstrates the energy intensity values of each pump in the baseline and new pump scenarios.

Table 6.4 The energy intensity values for each pump in Scenario I: baseline and Scenario II: new pump.

Pump	Scenario I: Baseline		Scenario II: New Pump	
	Percentage Utilization	Energy Intensity (Kw-hr/Mgal)	Percentage Utilization	Energy Intensity (Kw-hr/Mgal)
1	63.69	1,075.28	56.21	1,065.02
2	37.44	1,172.02	30.42	1,116.02
Proposed 1	-	-	100	248.44
TOTAL	-	2,247.3	-	2,429.48

6.2.3 Scenario II: new pump during fire flow

Feasibility and sustainability of the new pump scenario are investigated during fire flow condition. ISO (2008) minimum fire flow regulations are applied to simulate fire flow in the water distribution network. The fire flow is added to the dead-end node, which is located at Zone 5 (see Figure 6.7). The EPS is applied to the new pump scenario for 144 hour time period and results from hours 96 to 119 are used to calculate technical sustainability in terms of the nodal pressure and water age. In order to simulate the fire flow, a separate demand pattern is created in the EPANET software. In this demand pattern, the demand coefficient is modified at the simulation time steps 102 and 103 (i.e. also corresponds to peak demand hours) such that the demand at these time steps is 1,000 GPM. This demand pattern is assigned to the node where the fire flow is simulated.

6.2.3.1   The technical sustainability calculation of the new pump scenario during fire flow

The EPS result of the new pump scenario is visualized for the time steps from 101 to 105. Visualizing these time steps will enable to observe how the nodal pressure and water age parameters change due to the fire flow condition since the fire flow is simulated at the time steps 102 and 103. Figures 6.10 and 6.11 illustrate results of the EPS in the new pump scenario for the nodal pressure and water age parameters, respectively. As can be seen on Figure 6.11, nodal pressures at the entire water network have been adversely affected by fire flow simulation except the location corresponding to the Zone 3. On the other hand, the water age parameter remains stable during the simulation except at Zone 5, nodes in the close proximity to the simulated fire flow node (i.e. node ID 144), water age values deteriorate. The main reason is that during fire flow, the elevated storage tank located near the node ID 144 (see Figure 6.7 for the location of the storage tank) provides inflow to the water distribution network in order to sustain nodal pressures. The water quality at the elevated storage tank decreases the overall water quality at this section of the WDS.
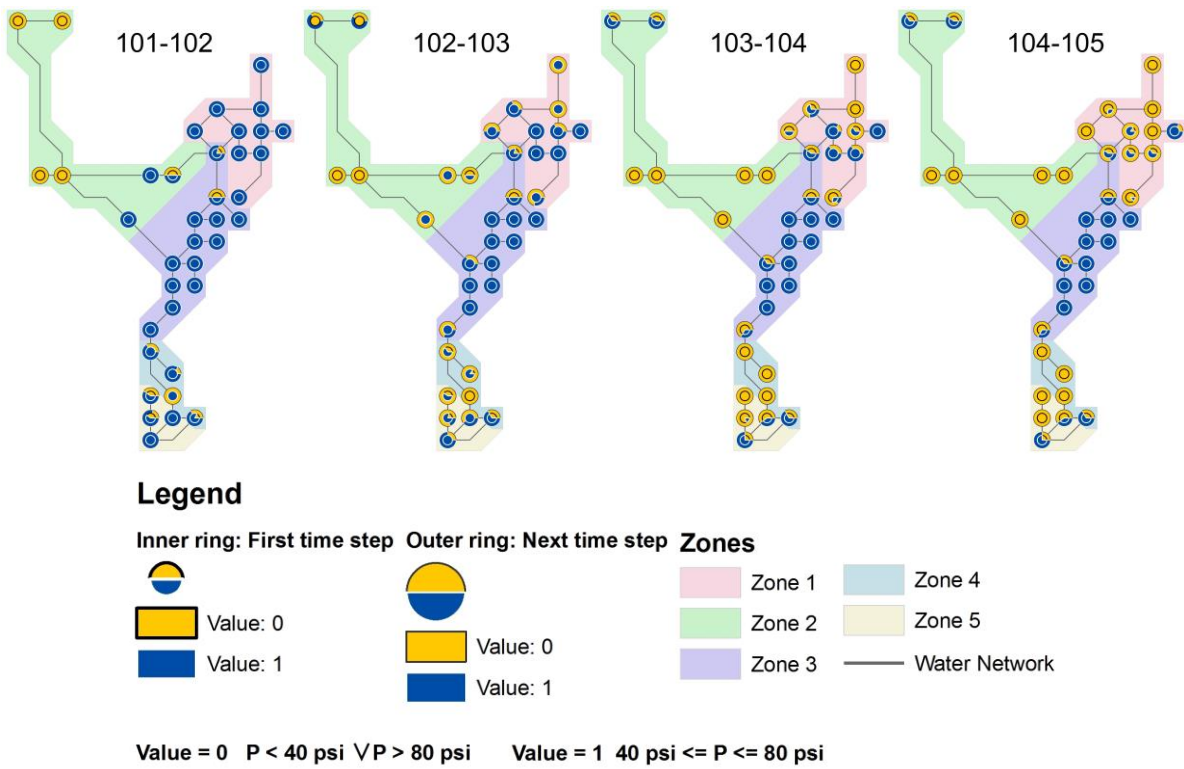
Figure 6.10 The EPS results for the nodal pressure parameter from time step 101 to 105 during fire flow condition.
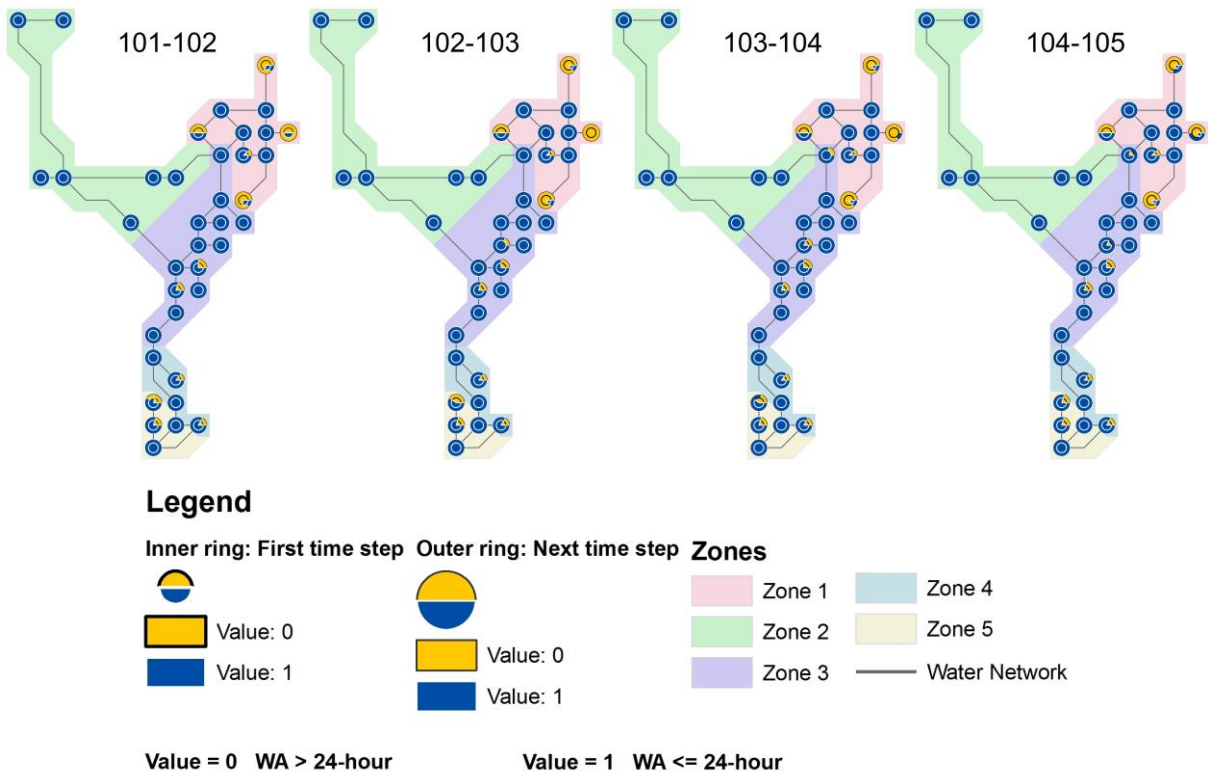
Figure 6.11 The EPS results for the water age parameter from time step 101 to 105 during fire flow condition.

The sustainability indices for the nodal pressure and water age parameters are calculated for each zone using the equation 4.7. Then, the sustainability indices of each zone for nodal pressure parameter are aggregated into the technical sustainability score (i.e. $SI_{network,pressure}$) using the equation 4.9. Similarly, the sustainability indices of each zone for the water age parameter are aggregated into the technical sustainability score (i.e. $SI_{network,waterage}$). Results of technical sustainability scores which are given in Table 6.5, showed that the $SI_{network,pressure}$ has decreased from 0.54 to 0.36. This indicates that the nodal pressure performance during the fire flow is highly affected by the fire flow requirement of 1,000 GPM for 2 hours.

Table 6.5 The technical sustainability results for Scenario II: new pump during fire flow.

Technical sustainability	$SI_{network,pressure}$	0.36	**Zones**	$SI_{pressure}$
			Zone 1	0.30
			Zone 2	0
			Zone 3	0.86
			Zone 4	0.27
			Zone 5	0.39
	$SI_{network,waterage}$	0.93	**Zones**	$SI_{waterage}$
			Zone 1	0.73
			Zone 2	1
			Zone 3	1
			Zone 4	0.99
			Zone 5	0.95

6.2.3.2   *The environmental sustainability of the new pump scenario during fire flow*

Environmental sustainability of the new pump scenario during the fire flow is considered by calculating the energy intensity and the total fresh water use in the water distribution network. In this scenario, base demands have not changed since only the current population and the water demand are considered. Therefore, total fresh water use is the same with the baseline scenario and approximately 385 GPM.

The energy intensity is taken from the energy report provided in the EPANET software for the entire simulation time. Results of environmental sustainability scores are given in Table 6.6. Outcomes of the fire flow simulation showed that the total energy intensity has increased from 2429.48 Kw-hr/Mgal to 2852.38 Kw-hr/Mgal in the new pump scenario due to the operation of the second proposed pump which serves only during the fire flow.

Table 6.6 Environmental sustainability for Scenario II: new pump under fire flow condition.

Total fresh water use (GPM)	385.56			
Total energy intensity (Kw-hr/Mgal)	2,852.38	Energy intensity for each pump	**PUMP**	**Energy intensity**
			1	1,087.49
			2	1,152.56
			Proposed 1	247.56
			Proposed 2	364.77

6.3   Scenario III: reclaimed water for fire flow scenarios

Scenario III: reclaimed water for fire flow scenarios are exploring the feasibility of using a non-potable WDS for the fire flow and non-potable indoor and outdoor water demands. It is assumed that the existing water network (i.e. potable WDS) will serve for the potable water demand at the Zone 5 and part of the Zone 4. Several demand variations (i.e. sub-scenarios) for the non-potable WDS are considered under this scenario as explained in the methodology section (see Table 4.3 in Chapter 4).

Water demand and wastewater flows are calculated in order to verify the wastewater availability and wastewater recycling potential to meet the non-potable water demand. In order to identify the amount of wastewater that can be recycled, residential wastewater reclamation examples are investigated. In one example, a high-rise residential building in New York uses recycled wastewater for toilet flushing and cooling water by three-stage membrane bioreactor (MBR), ozone oxidation for color removal and ultraviolet disinfection technologies. In this example system approximately 46% of the base demand is recycled to meet the non-potable water demand (Zavoda 2005). Therefore, it is assumed that 46% of total base demand will be reused using MBR technologies in the dual WDS.

Flow calculations are given in Table 6.7. Based on Table 6.7, the non-potable water demands in Scenario III options A and C are 59,393 GPD (approximately 225 m^3/d) while in Scenario III options B and D, it is 23,756 GPD (approximately 90 m^3/d). Total reclaimed water potential in the entire study area is 255,395 GPD (approximately 967 m^3/d), 118,013 GPD (approximately 447 m^3/d) of this can be produced using the wastewater only from zones 4 and 5. Results of flow calculations show that the amount of wastewater from zones 4 and 5 is sufficient to meet the demand in the non-potable WDS. Using wastewater only from zones 4 and 5 might be beneficial in terms of avoiding the water transportation with on-site recycling and storage facilities.

Table 6.7 Water demand and reclaimed water potential calculation.

Zone	Basedemand (GPD)	Population	Potential reclaimed water (GPD)
Zone 1	67,680	376	31,133
Zone 2	8,496	47	3,908
Zone 3	222,480	1,236	102,341
Zone 4	187,733	1,043	86,357
Zone 5	68,818	382	31,656
TOTAL	555,206	3,084	255,395
Zone 4 + Zone 5	256,550		**118,013**
Total Reclaimed Water Basedemand (GPD)			
Option A	59,393		
Option B	23,756		
Option C	59,393		
Option D	23,756		

6.3.1 Design of the reclaimed water distribution network

The dual water network is designed as a tree structured distribution system (see Figure 6.13). The cost for a PVC type is investigated for different pipe sizes. Costs of these pipes are found considering AWWA specifications C-900 (12-inch and under). Material, labor and equipment costs together with the backfill cost are included into the pipe cost constraints.

The main reason that PVC material is considered for pipe design is that the ductile iron pipe type is more expensive than the PVC material. For example, total cost of the ductile iron in 6-inch pipes is 26.47 $ per ft while the PVC cost for the same size is 13.42$ per ft (JM Eagle 2011). In this study, piping materials in the non-potable WDS is assumed to be the PVC.

The outline of the non-potable WDS together with the potable network is given in Figure 6.13. A linear programming approach is used to determine the size of pipes and pumping head cost. The GAMS software is used to implement the optimization method (see Chapter 4, Section 4.4.4.2). In the optimization approach, only 4 different commercial pipe sizes are considered: 6 inch, 8 inch, 10 inch and 12 inch. The input file for the GAMS is provided in Appendix 3. The aim of the pipe layout is to minimize cross connections between the non-potable water mains and the potable WDS. Therefore, the dual water network is designed as a tree structure distribution system.
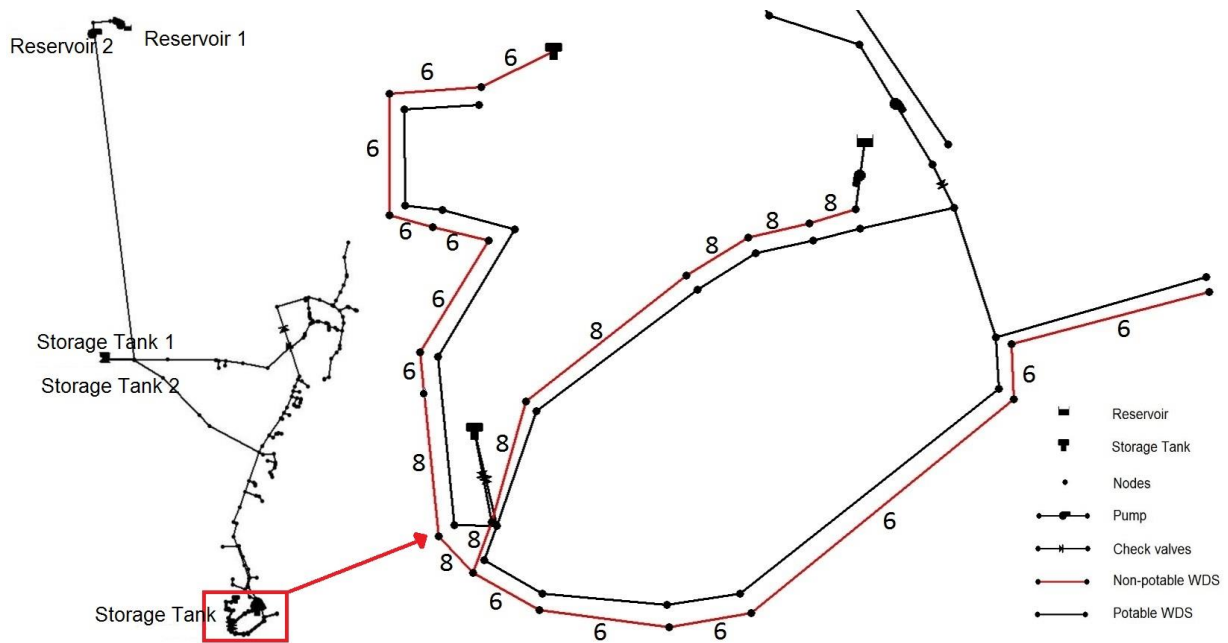
Figure 6.12 Potable and non-potable water networks.

Elevation of the study area ranges between 475 and 559 ft (approximately 144 m and 160 m, respectively). The long-term storage for the non-potable WDS is proposed to be located at one of the lowest points on the study area (i.e. elevation of 485 ft (approximately 147 m)). In order to meet fire flow requirements in the worse-case scenario, junctions which are located at one of the highest and the lowest elevations are chosen to optimize pipe sizes and the cost of the non-potable water network. These junctions are also located at dead ends of the non-potable WDS (see Figure 6.13). According to the ISO (2008) fire flow regulation, a WDS should be designed to meet minimum 1,000 GPM (63.1 liter/s) fire flow sustaining 20 psi (14.1 mH$_2$O) pressure head. Therefore, total fire flow of 1,000 GPM (63.1 liter/s) is added at junctions which are located at elevations of 475 ft and 525 ft (approximately 144 m and 160 m), respectively.

As mentioned before, four candidate pipe sizes are considered for each link while designing the non-potable WDS (i.e. 6, 8, 10, and 12 inches with the cost of 13.42 $/foot, 17.86 $/foot, 22.68 $/foot, 27.30 $/foot, respectively). Due to the fire flow requirements in the ISO 2008 regulation, pipe sizes smaller than 4 inches are eliminated. Minimum required nodal pressure at all nodes in the dual WDS is 20 psi (14.1 mH$_2$O) while maximum pressure head is 80 psi (56.2 mH$_2$O). The result of the optimization model for pipe sizes and pipe lengths are given in Figure 6.14 for scenario options A – B – C – D. Pipe sizes in options A and B vary between 6-inch and 8-inch while all pipes in the hybrid non-potable WDS (Option D) are 6-inch since base demands and the fire flow are smaller than other scenario options. Total costs for Scenario III (i.e. the non-potable WDS) options A, B, C, and D (see Table 4.9 for the scenario properties) are approximately $81,700, $81,000, $73,100, and $73,000, respectively.
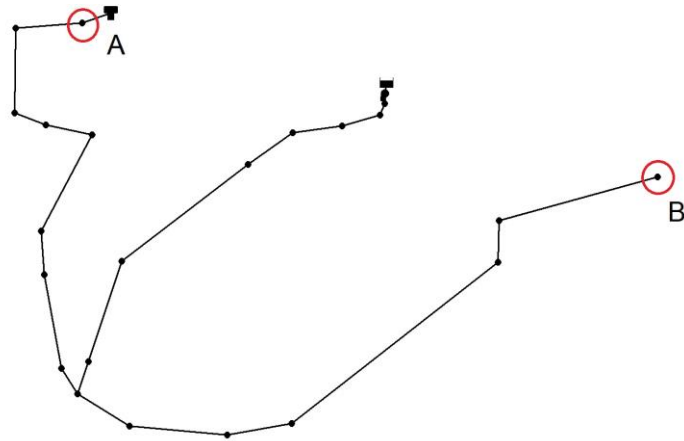
Figure 6.13 Simulated fire flow locations for the LP optimization model A. Elevation of 525 ft, B. Elevation of 475 ft.

6.3.2 The technical sustainability calculation of reclaimed water for fire flow scenario options

After pipe sizes for all of the reclaimed water for fire flow scenario options are determined, the EPS is applied for 144 hours to both potable and non-potable WDSs of each scenario option. Note that the potable and the non-potable water networks are modelled separately and EPSs are operated distinctly in the EPANET software.
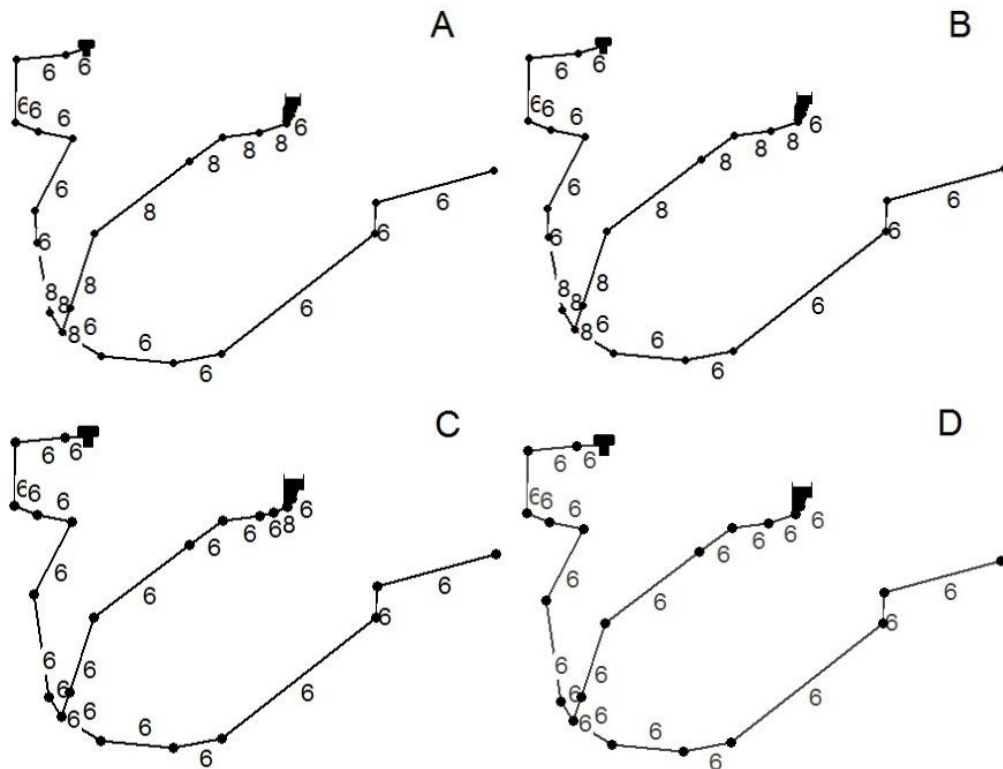
Figure 6.14 Optimization model pipe sizes results for the non-potable WDS in scenario options A, B, C, and D.

6.3.2.1   Scenario III: Option A

Based on the requirements of each scenario option, base demands are reduced in the potable WDS at Zone 5 and the part of Zone 4 since the non-potable water network serves for the fire flow and the non-potable indoor and outdoor water demand. In order to calculate the technical sustainability of option A, results of the EPS from time steps 96 to 119 are taken into account. Results of the simulation from time steps 101 to 105 for the nodal pressure and the water age parameters are illustrated in figures 6.15 and 6.16, respectively.
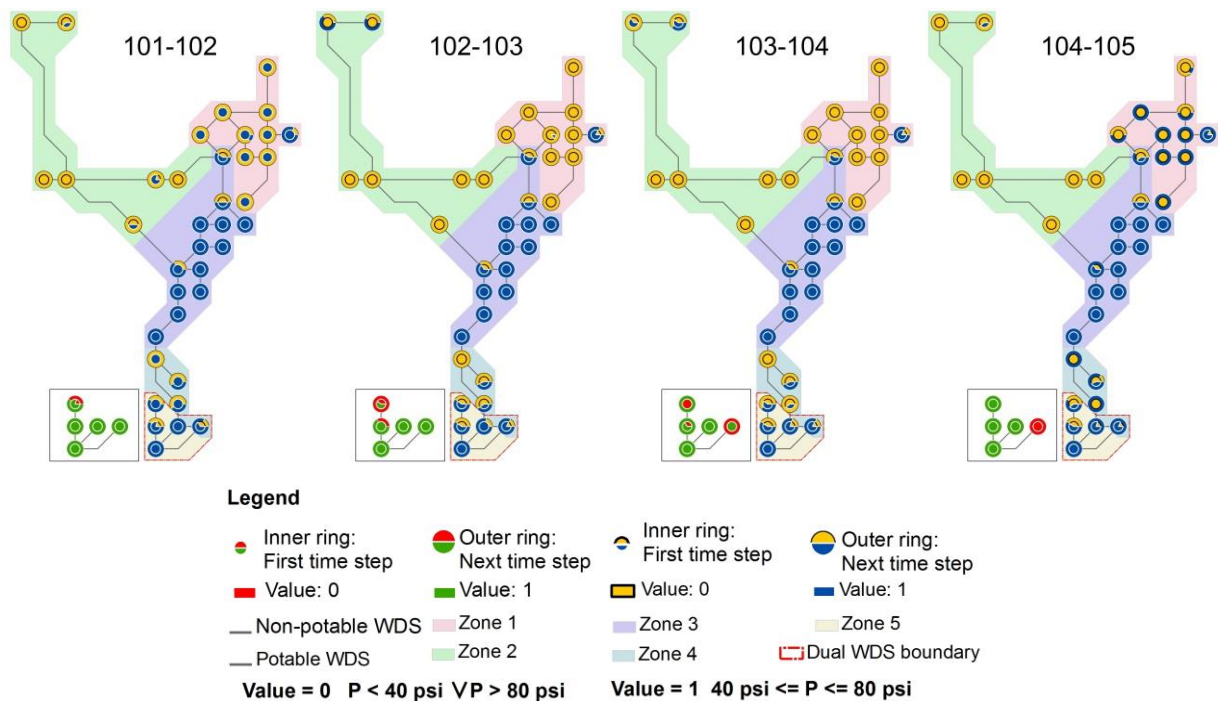
Figure 6.15 The EPS results for the nodal pressure parameter from time step 101 to 105 during fire flow condition.

As can be seen from Figure 6.16, the water age parameter at Zone 5 in the potable WDS deteriorates due to decreasing base demands (i.e. 75 % reduction of base demands) in the potable water network. This problem can be solved by reducing the pipe diameters in the potable water network. Large pipe diameters and low base demands at nodes lead to increasing water ages and decreasing the $SI_{waterage}$. The SI calculations for each zone as well as the technical sustainability of $SI_{network,pressure}$ and $SI_{network,waterage}$ for Scenario III: option A are given in Table 6.8.

The $SI_{network,k}$ is calculated using Equation 4.9 for the nodal pressure and water age parameters separately. $SI_{pressure}$ and $SI_{waterage}$ for each zone are calculated using equation 4.7 which is explained in detail in the Chapter 4 of this dissertation. For the reclaimed water for fire flow scenario option A the technical sustainability in terms of the nodal pressure and water age parameters are 0.62 and 0.77, respectively.
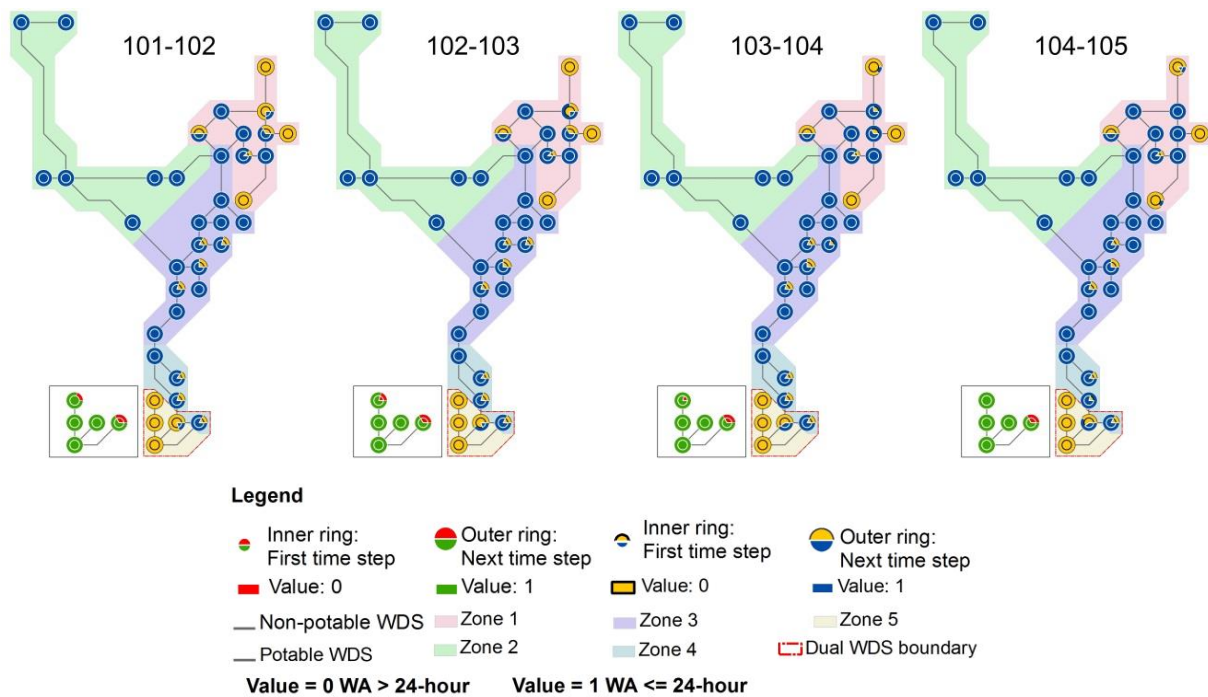
Figure 6.16 The EPS results for the water age parameter from time step 101 to 105 during fire flow condition.

Table 6.8 The technical sustainability calculations for the Scenario III Option A in potable and non-potable WDSs.

Scenario	Score	$SI_{pressure}$	$SI_{waterage}$
Scenario III: Option A	Zone 1	0.47	0.54
	Zone 2	0.08	1.00
	Zone 3	1.00	0.99
	Zone 4	0.61	0.99
	Zone 5	0.71	0.09
	Dual System	0.84	0.99
	$SI_{network,k}$	**0.62**	**0.77**

6.3.2.2 *Scenario III: Option B*

In the scenario option B, the non-potable WDS is serving for the fire flow and the outdoor water demand. Outdoor water demand is assumed to be 30 % of the current base demand. Results of the EPS from time steps 101 to 105 for the nodal pressure and the water age parameters are given in figures 6.17 and 6.18, respectively. The water age parameter at Zone 5 in the potable WDS slightly increases in this scenario since base demands in the potable system are decreased only by 30 %. In addition to sustainability indices of each zone in terms of the nodal pressure and water age, the technical sustainability calculations of the entire network for the scenario option B for the nodal pressure and water age parameters are given in Table 6.9.
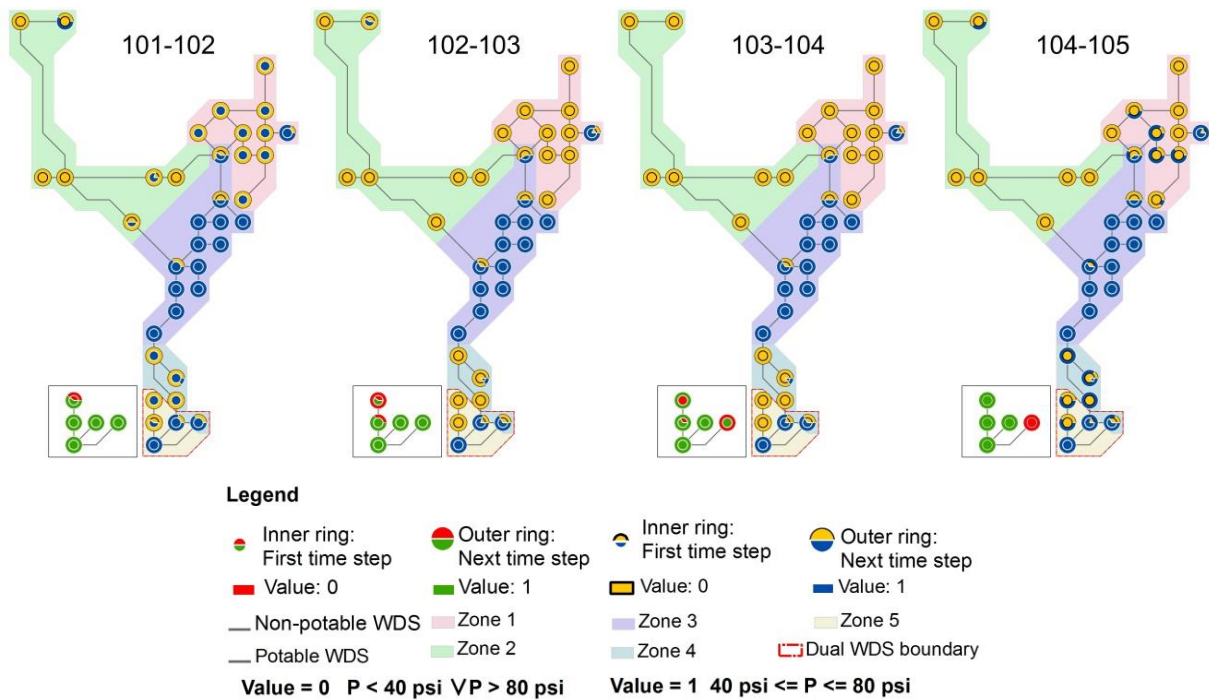
Figure 6.17 The EPS results for the nodal pressure parameter from time step 101 to 105 during fire flow condition.
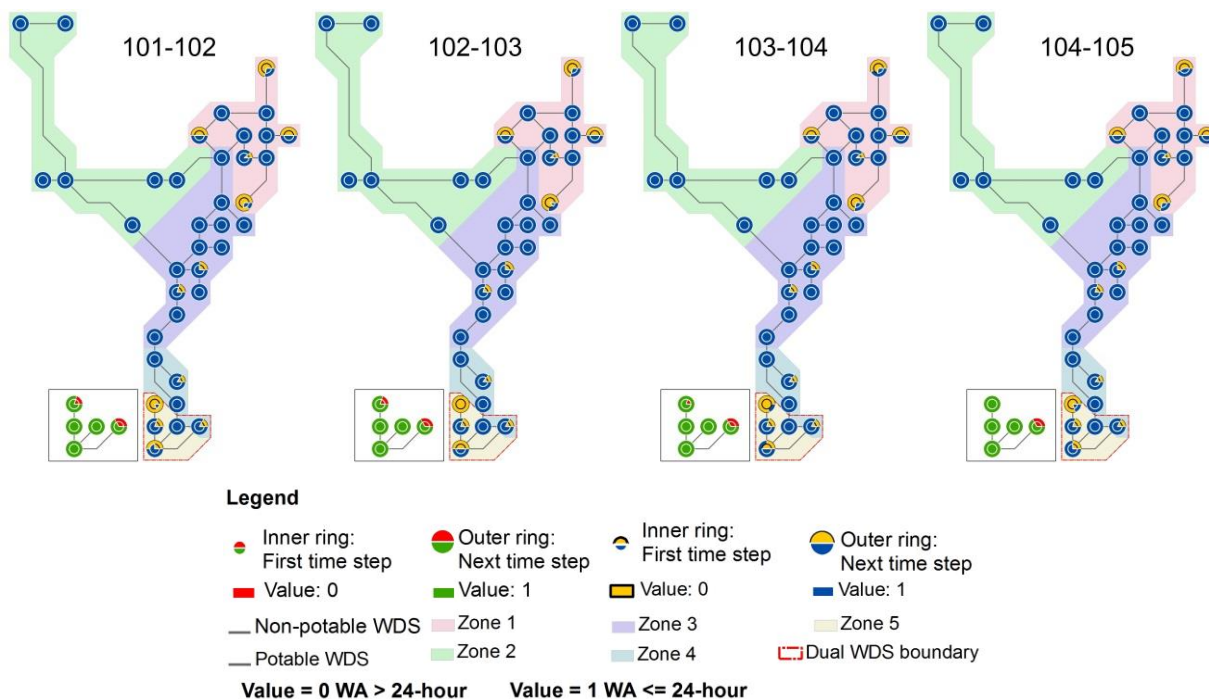
Figure 6.18 The EPS results for the water age parameter from time step 101 to 105 during fire flow condition.

Table 6.9 The technical sustainability calculations for the Scenario III Option B in potable and non-potable WDSs.

Scenario	Zone	$SI_{pressure}$	$SI_{waterage}$
Scenario III: Option B	Zone 1	0.42	0.74
	Zone 2	0.08	1.00
	Zone 3	0.97	1.00
	Zone 4	0.51	0.99
	Zone 5	0.61	0.72
	Dual System	0.82	0.98
	$SI_{network,k}$	0.57	0.91

6.3.2.3 *Scenario III: Option C*

A hybrid system for the fire flow and the non-potable water demand is proposed in this scenario. Figures 6.19 and 6.20 illustrate results of the EPS for the nodal pressure and water age parameters, respectively. Results for the technical sustainability calculations for the nodal pressure and water age parameters as well as sustainability indices of each zone in terms of the nodal pressure and water age are given in Table 6.10. In Scenario III: Option C, the fire flow should be met using both potable and non-potable water distribution networks, while the non-potable WDS should serve for the both non-potable indoor and outdoor water demand which is assumed to be 75 % of the current base demand at Zone 5 and the part of Zone 4. The fire flow and base demand assumptions are provided in Table 4.3 in the methodology section of this dissertation.
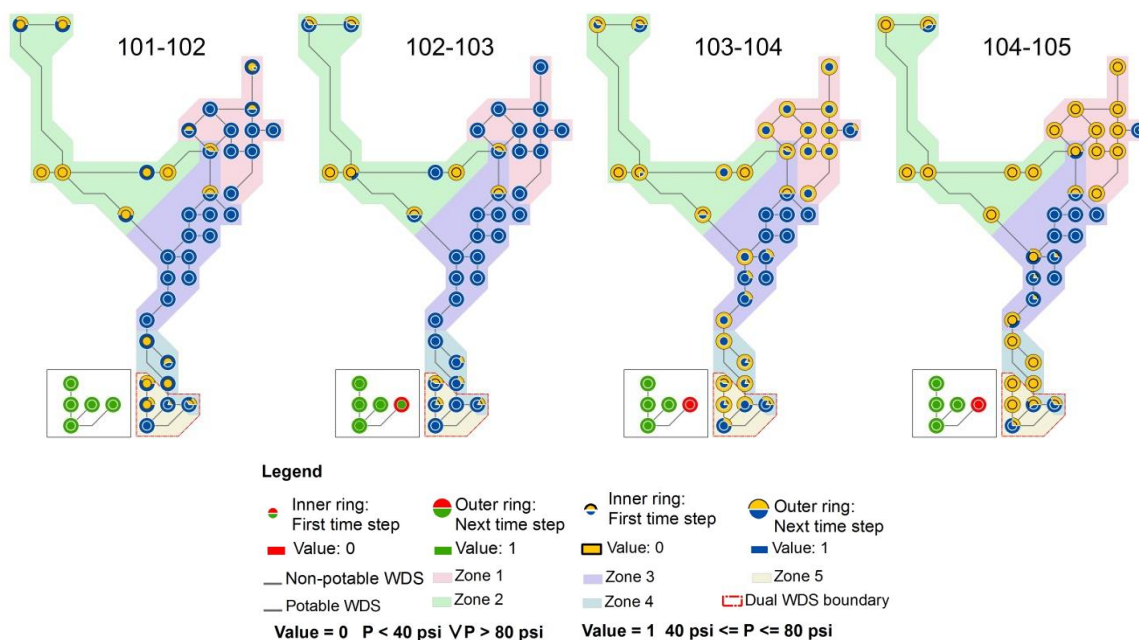
Figure 6.19 The EPS results for the nodal pressure parameter from time step 101 to 105 during fire flow condition.
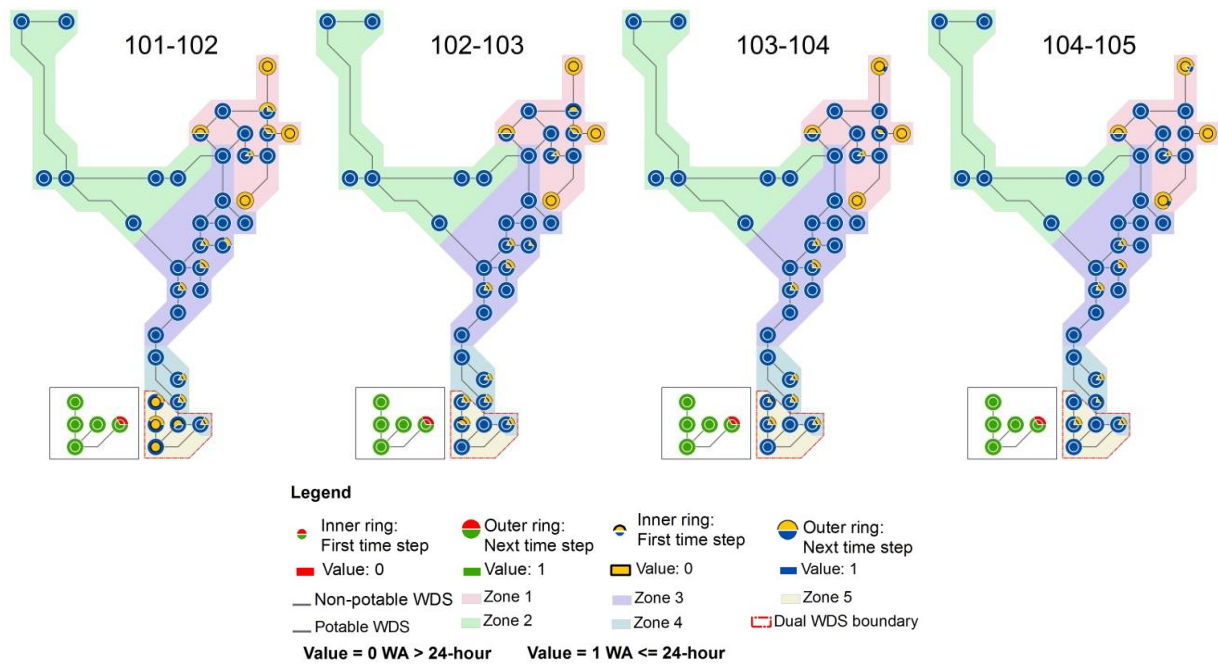
Figure 6.20 The EPS results for the water age parameter from time step 101 to 105 during fire flow condition.

Table 6.10 The technical sustainability calculations for the Scenario III Option C in potable and non-potable WDSs.

Scenario	Zone	$SI_{pressure}$	$SI_{waterage}$
Scenario III: Option C	Zone 1	0.41	0.57
	Zone 2	0.07	1.00
	Zone 3	0.91	1.00
	Zone 4	0.42	0.99
	Zone 5	0.54	0.37
	Dual System	0.88	0.99
	$SI_{network,k}$	**0.54**	**0.82**

6.3.2.4 *Scenario III: Option D*

In this scenario option, a hybrid system for the fire flow and the non-potable water demand is proposed with an alternative base demand assumption for the non-potable WDS. Similar to Scenario III Option C, the fire flow is met using both the potable and the non-potable water distribution networks. Figures 6.21 and 6.22 illustrate results of the EPS for the nodal pressure and water age parameters, respectively.
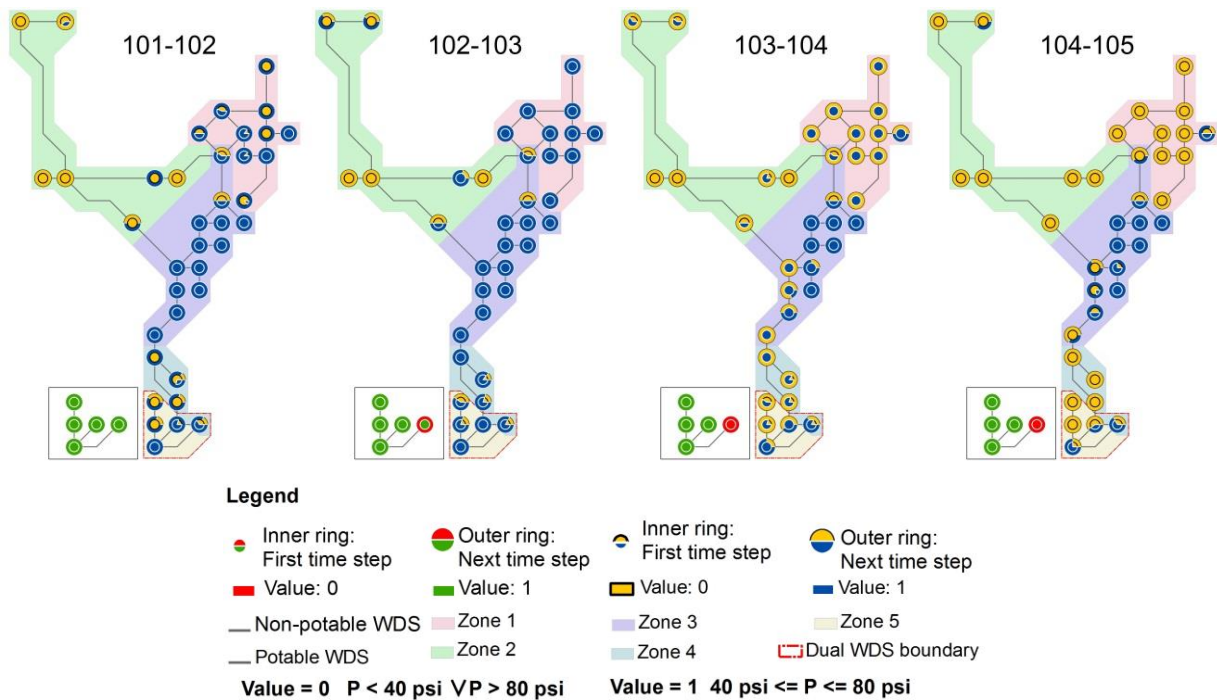
Figure 6.21 The EPS results for the nodal pressure parameter from time step 101 to 105 during fire flow condition.
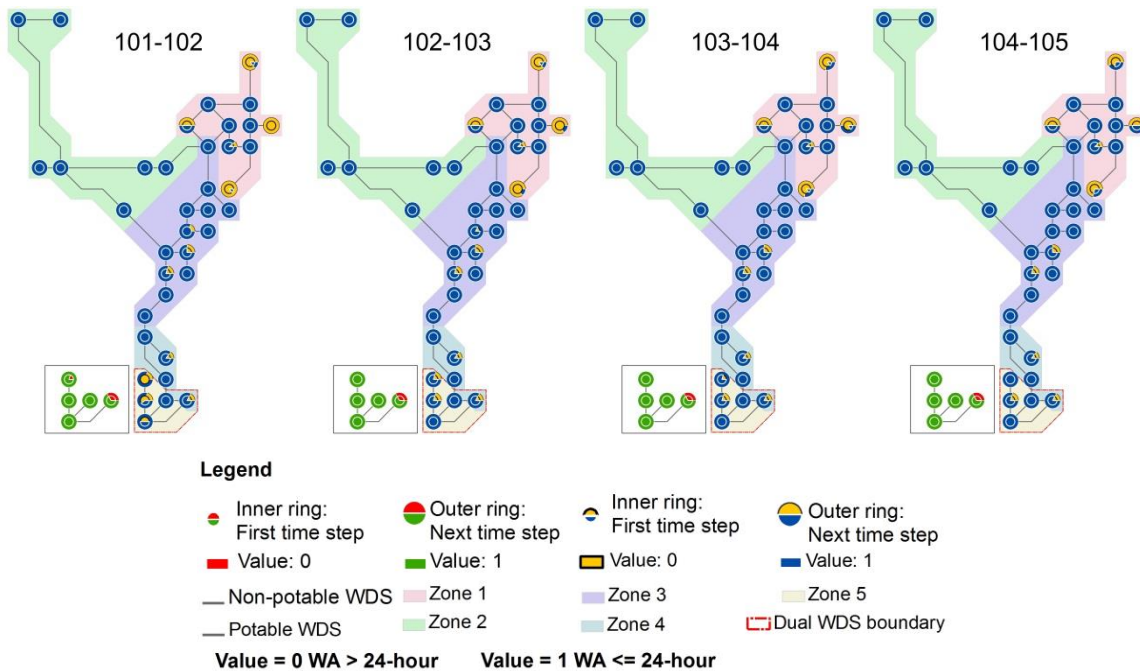
Figure 6.22 The EPS results for the water age parameter from time step 101 to 105 during fire flow condition.

The difference with the Scenario III Option C is that the non-potable water network serves for the outdoor irrigation only. The amount of the outdoor irrigation in this

scenario is identified as 30 % of the current base demand at Zone 5 and part of Zone 4. The fire flow and the base demand assumptions are provided in Table 4.3 in the methodology section. In this scenario option, $SI_{network,pressure}$ and $SI_{network,waterage}$ scores (i.e. technical sustainability scores) are 0.50 and 0.90. Details of the technical sustainability for the nodal pressure and water age parameters are presented in Table 6.11.

Table 6.11 The technical sustainability calculations for the Scenario III Option D in potable and non-potable WDSs.

Scenario	Zone	$SI_{pressure}$	$SI_{waterage}$
Scenario III Option D	Zone 1	0.29	0.68
	Zone 2	0.07	1.00
	Zone 3	0.89	1.00
	Zone 4	0.34	0.99
	Zone 5	0.52	0.77
	Dual System	0.88	0.98
	$SI_{network,k}$	0.50	0.90

6.3.3 The environmental sustainability calculation of Scenario III reclaimed water for fire flow scenario options

Energy intensity and total fresh water use in the reclaimed water for fire flow scenario options are considered as environmental sustainability criteria and calculated for the dual WDS and the potable water network. Previously, the base demand for the new pump scenario was the same with the baseline scenario, since the population of the current water network was not altered and the water network sustainability was improved by adding new network elements. However, in the reclaimed water for fire flow scenarios, base demands have changed since the non-potable WDS is proposed for the Zone 5 and the part of Zone 4. The dual water network serves the reclaimed water for the non-potable indoor and outdoor water demand. Base demands of the potable WDS in Scenario III options A and C are reduced 75 % while in scenario options B and D, 30 % of the base demand is met using the reclaimed water.

The energy intensity values for each scenario option are taken from energy reports provided in the EPANET software. Note that the energy intensity values are for the entire simulation time (i.e. 7 days) for both potable and non-potable WDSs. Results of environmental sustainability scores are given in Table 6.12. The results showed that the energy intensity of the hybrid fire flow scenarios (i.e. Scenario III options C and D) are higher than the other reclaimed water for fire flow scenario options. This is because, in the hybrid scenarios, 50 % of the minimum fire flow requirement (i.e. 500 GPM) is met using the potable WDS which is more energy intensive since the main

reservoir is located further away from the simulated fire flow node. Energy intensity values may change according to the simulated fire flow location. In addition, the other factors such as using different pump curves and pumping schedule may alter the energy intensity of the WDS.

Table 6.12 The environmental sustainability results for the scenario the reclaimed water for fire flow scenario options.

Scenario III Options	Total fresh water use (GPM) (equivalent liter/s)	Total energy intensity (Kw-hr/Kgal)
Option A	344.35 (21.7)	3,181.69
Option B	369.08 (23.3)	3,199.51
Option C	344.35 (21.7)	3,201.87
Option D	369.08 (23.3)	3,262.14

6.4 Scenario comparison

6.4.1 Multi-criteria decision analysis for the current population scenarios

In order to analyze and compare each scenario with respect to the identified technical and environmental sustainability criteria, the MCDA is utilized. The MCDA focuses on the feasibility comparison of fire flow scenarios. The simple additive weighting aggregation method is used to conduct the MCDA which consists of the following stages. First, the raw data (i.e. each technical and environmental sustainability criterion) is normalized using a linear scale transformation methodology. Then, weights which represent the importance of each criterion are calculated. Finally, the simple additive weighting method is used to finalize the scores of each decision alternative (i.e. each scenario).

6.4.2 Normalization of each criterion

Normalizing raw data is a necessary step in order to proceed further with the MCDA and to compare results of each alternative scenario. Raw scores of technical and environmental sustainability criteria for each scenario are standardized using a linear transformation technique which is explained in detail in Chapter 4, Section 4.4.2. Technical sustainability criteria are standardized using the "benefit criterion" equation 4.16, and environmental sustainability criteria are standardized using the "cost criterion" (i.e. equation 4.17). Raw values together with the normalized scores are given in Table 6.13.

6.4.3 Defining weights for each criterion

Weights for each criterion are defined using the "rank sum" algorithm which is explained in detail in Chapter 4, Section 4.5.3. As mentioned before, four ranking options are considered in order to prioritize each criterion at least once. In other words, in each ranking option, the highest weight is assigned to a different criterion.

Table 6.13 Raw data and normalized scores for the technical and environmental sustainability criteria for the current population and water demand scenario.

	Scenarios in Fire Flow Conditions	Technical sustainability		Environmental sustainability	
		$SI_{network,pressure}$	$SI_{network,waterage}$	Total Fresh water Use (GPM)	Energy Intensity (Kw-hr/Mgal)
Raw values	New Pump	0.36	0.93	385.56	2,852.38
	Option A	0.62	0.77	344.35	3,181.69
	Option B	0.57	0.91	369.08	3,199.51
	Option C	0.54	0.82	344.35	3,201.87
	Option D	0.50	0.90	369.08	3,262.14
Normalized	New Pump	0	1	0	1
	Option A	1	0	1	0.20
	Option B	0.82	0.83	0.40	0.15
	Option C	0.70	0.31	1	0.15
	Option D	0.54	0.81	0.40	0

Equation 4.18 is used to calculate the weights for each ranking option. The ranked order for environmental and technical sustainability criteria is given in Table 4.7. In addition, numerical weights for environmental and technical sustainability criterion are given for each ranking option in Table 4.8.

In Table 6.13, each criterion is normalized for all scenarios. Due to the normalization, for each criterion, one scenario is assigned a value of "0" and one scenario is assigned a value of "1". For example, the "new pump" scenario has the value of "0" for the $SI_{network,pressure}$ criterion. This means that the "new pump" scenario has the lowest score in terms of $SI_{network,pressure}$ criterion among all the scenario alternatives. On the other hand, Scenario III option A has the value of "1" since this scenario option had the highest $SI_{network,pressure}$ score. Note that, $SI_{network,pressure}$ criterion is normalized using a "benefit criterion" procedure (i.e. Equation 4.16). Total fresh water use and energy intensity criteria are normalized using the "cost criterion" procedure (i.e. equation 4.17).

6.4.4 Simple additive weighting methodology

The simple additive weighting aggregation operator is used to evaluate final scores of each scenario alternative. Mainly, the identified weights are multiplied with the corresponding normalized criterion for each scenario and all of the environmental and technical criteria are aggregated into final scores. Equation 4.19 which is presented in the methodology chapter (i.e. Chapter 4 Section 4.4.3) is used for this purpose. Table 6.14 represents the scores of each criterion for each ranked order. In this table, normalized values of each technical and environmental sustainability criterion are multiplied by the weights with respect to its identified ranked order. The highest total score in each ranked order represents the most favorable scenario.

Table 6.14 Total scores for each ranking option for the current population and water demand scenarios in fire flow conditions.

	Scenario II:	$SI_{network,pressure}$	$SI_{network,waterage}$	Energy Intensity	Total Freshwater Use	Total Score
RANK 1	New Pump	0	0.3	0.1	0	0.4
	Option A	0.4	0	0.02	0.2	0.62
	Option B	**0.33**	**0.25**	**0.02**	**0.08**	**0.67**
	Option C	0.28	0.09	0.01	0.2	0.59
	Option D	0.22	0.24	0	0.08	0.54
RANK 2	New Pump	0	0.4	0.1	0	0.5
	Option A	0.3	0	0.02	0.2	0.52
	Option B	**0.25**	**0.33**	**0.02**	**0.08**	**0.67**
	Option C	0.21	0.12	0.01	0.2	0.55
	Option D	0.16	0.33	0	0.08	0.57
RANK 3	New Pump	0	0.1	0.3	0	0.4
	Option A	**0.2**	**0**	**0.06**	**0.4**	**0.66**
	Option B	0.16	0.08	0.05	0.16	0.45
	Option C	0.14	0.03	0.04	0.4	0.61
	Option D	0.11	0.08	0	0.16	0.35
RANK 4	New Pump	0	0.1	0.4	0	0.5
	Option A	**0.2**	**0**	**0.08**	**0.3**	**0.58**
	Option B	0.16	0.08	0.06	0.12	0.43
	Option C	0.14	0.03	0.06	0.3	0.53
	Option D	0.11	0.08	0	0.12	0.31

Note that, the most favorable scenario might change since the prioritized criterion changes in each ranked order. For example, in the ranked option 1, the highest weight is assigned to the technical sustainability criterion of $SI_{network,pressure}$, and the

most feasible scenario when $SI_{network,pressure}$ is the highest priority is the scenario option B (i.e. using reclaimed water for fire flow and outdoor irrigation). On the other hand, the option A is the most favorable scenario in ranking options 3 and 4 which prioritize the environmental sustainability criteria. Even though options A and B have high scores in the ranked order 3 and 4, and the ranked order 1 and 2, respectively, the normalized criteria show that using the reclaimed WDS for the fire flow and the non-potable water demands is more energy intensive than the new pump scenario.

6.5   An interactive urban water system planning tool

A prototype is developed for the current population and water demand scenarios in order to improve the DSS. The main goal of creating an interactive tool is to facilitate the decision-making process and communicate with the data. The visualization approach proposed in this dissertation improves the visibility of the demand points (i.e. nodes) and emphasizes the satisfactory and unsatisfactory thresholds which are defined for the nodal pressures and water ages separately. In addition, it provides insight about the reliability, resiliency, and vulnerability performance criteria (see Figure 5.4 in Chapter 4).

However, using the visualization approach requires radical changes in the appearance of the urban WDS. Decision makers and/or experts should be able to relate to the proposed visualization approach with the original data set. Therefore, the prototype provides the original data set together with the circle view representation. It is easy to select a scenario and visualize the results as well as observing the technical and environmental sustainability criteria. Figure 6.23 illustrates how to select a scenario using a combo box at the topmost part of the tool (see Figure 5.6-B).
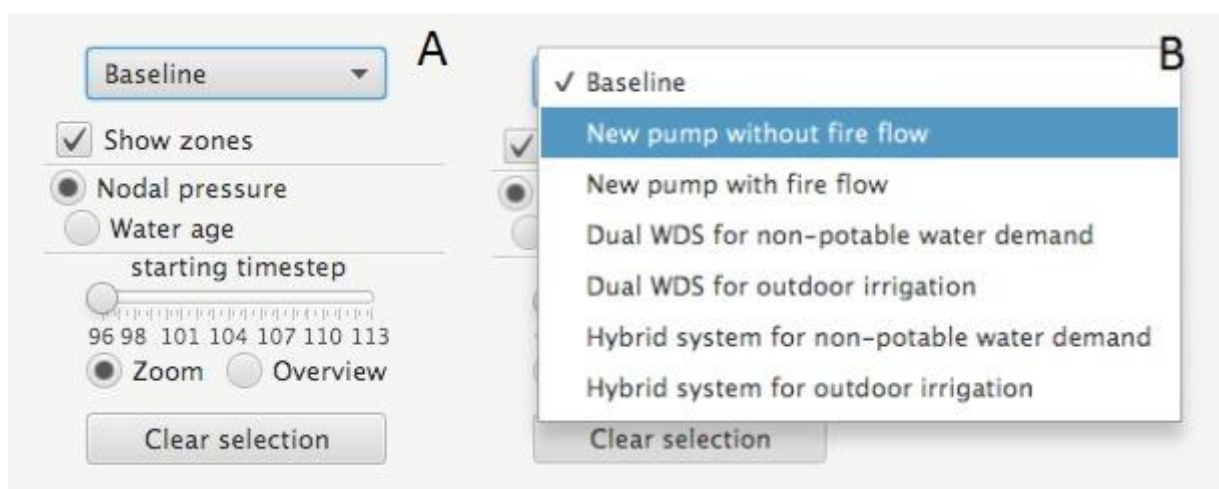
Figure 6.23 Selecting a scenario. A. An overview for interaction tools. B. The activating scenario selection.

This tool provides easy access to each scenario. Decision makers and/or experts are able to switch between scenarios and visualize the results for each scenario. The scenario names appeared in the urban water system planning tool and corresponding names used in this dissertation are given in Table 6.15.

Table 6.15 Scenario names.

Scenarios in the urban water system planning	Corresponding names
Baseline	Scenario I: Baseline
New pump without fire flow	Scenario II: New pump
New pump with fire flow	Scenario II: New pump during fire flow
Dual WDS for non-potable water demand	Scenario III: Option A
Dual WDS for outdoor irrigation	Scenario III: Option B
Hybrid system for non-potable water demand	Scenario III: Option C
Hybrid system for outdoor irrigation	Scenario III: Option D

6.5.1 Interaction example

The original data can be seen in the secondary data frame (Figure 5.6-C) when a circle view at the main data frame (Figure 5.6-A) is selected (see Figure 6.24). Once the radio button "Zoom" is selected, a circle view at the main data frame, the secondary data frame will zoom into the corresponding nodes that the selected circle view represents. In addition, selecting a circle view will update the graph at the bottom of the tool (see Figure 5.6-F). The graph will illustrate actual values for the selected nodes of the selected parameter, in this case the nodal pressure parameter (see Figure 6.25). For example in Figure 6.25, the nodal pressure parameter is selected and the graph provides all the values for the entire simulation time (i.e. from hour 96 to 119) for the selected circle view. Note that the color code for the graph lines and the color code for the nodes at the secondary data frame concur. For example, if the node at the secondary data frame is "yellow", the line in the graph that represents that particular node is also "yellow".

In addition, decision makers and/or experts might observe the original data in the secondary data frame using the "Overview" radio button. Selecting a circle view would highlight the pipes at the secondary data frame in full scale. In Figure 6.26, highlighted edges are corresponding to the selected circle view.
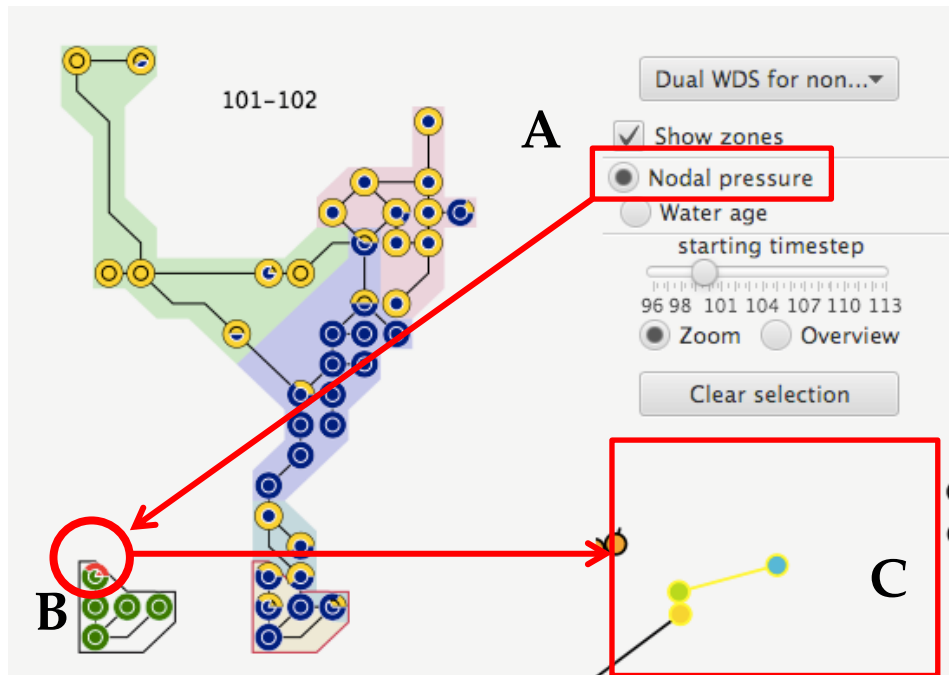
Figure 6.24 A. Selecting a circle view using the "Zoom" button. B. Selecting a circle view at the main data frame. C. Observing the corresponding nodes at the secondary data frame.
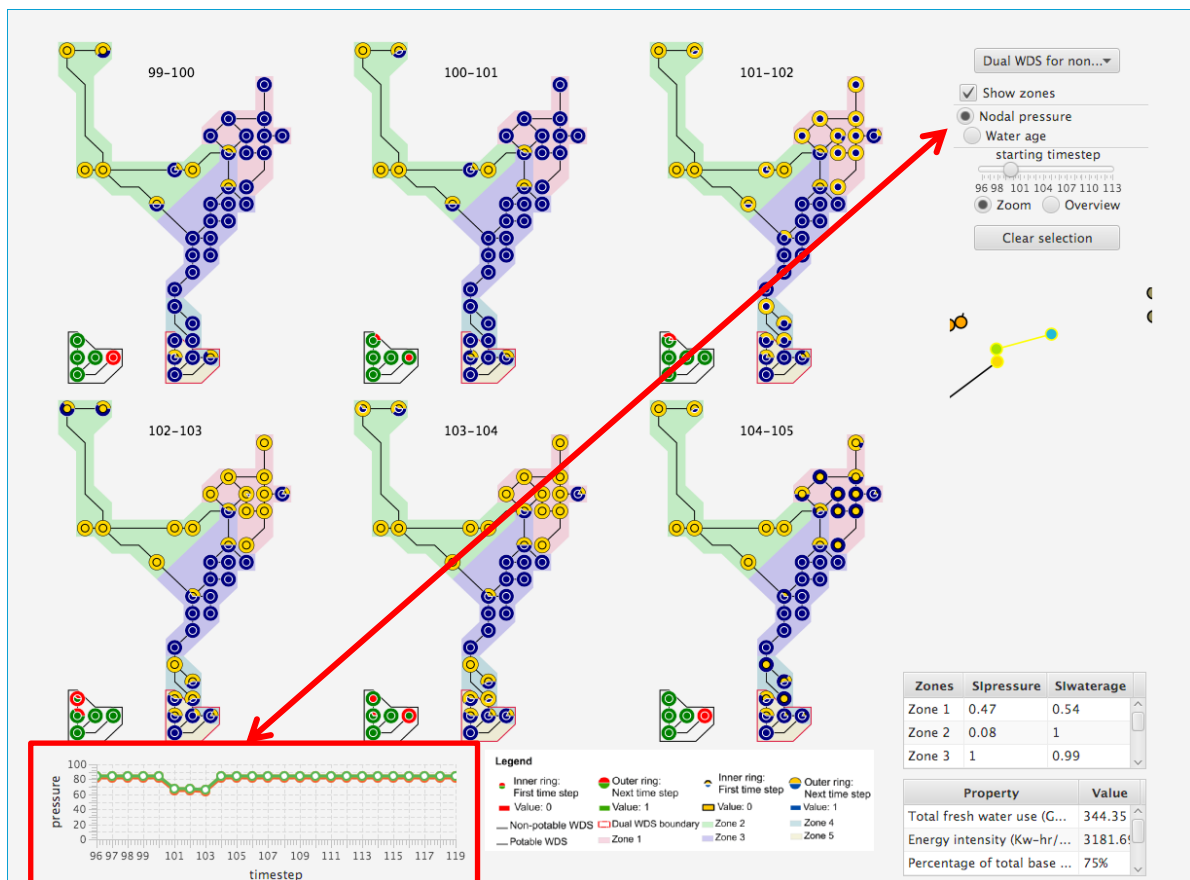
Figure 6.25 Creating graphs for the nodal pressure parameter.
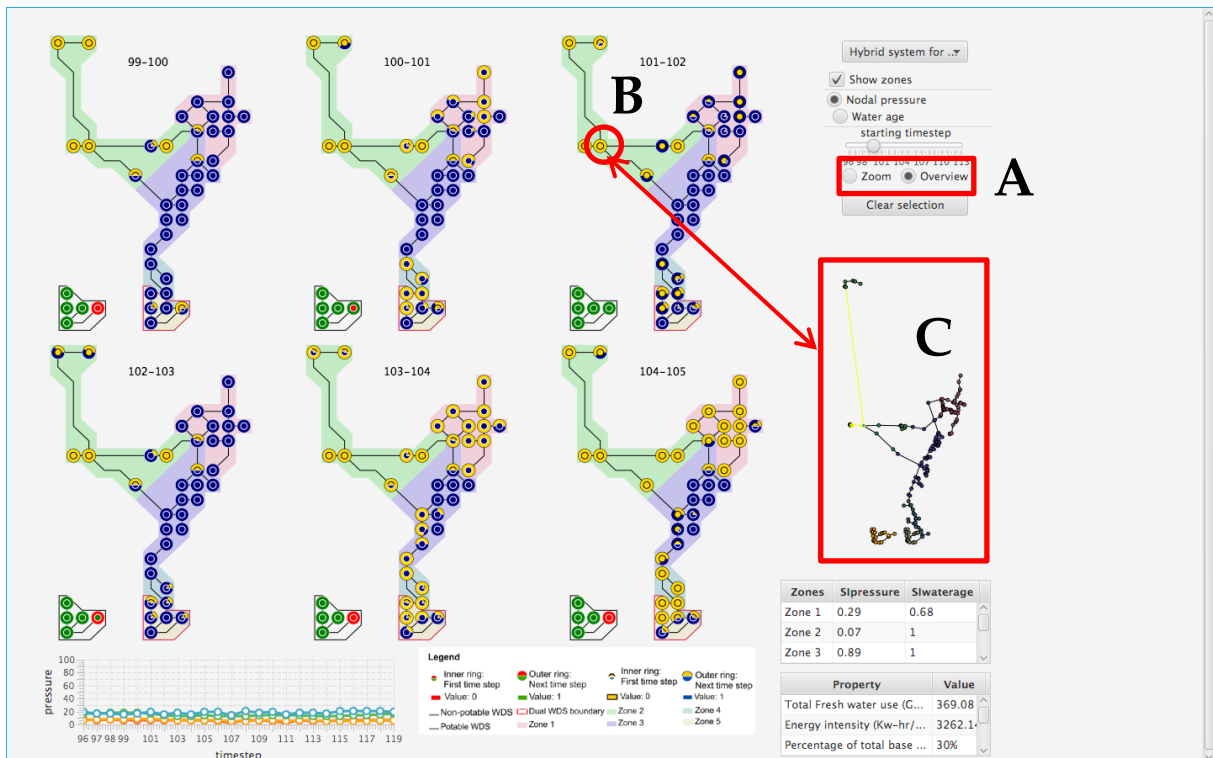
Figure 6.26 A. Selecting a circle view using the "Overview" tool. B: Selecting a circle view at the main data frame. C. Observing the corresponding nodes at the secondary data frame.

6.6 Conclusion

The current water distribution network is analyzed in terms of the identified technical and environmental sustainability criteria. First, the technical sustainability of the current WDS is analyzed and problems with the current system as well as problematic locations are determined. The technical sustainability scores are calculated based on reliability, resiliency and vulnerability performance criteria, while environmental sustainability criteria are identified based on literature review. In order to find alternative solutions to the identified problems in the baseline scenario, two distinctive approaches are proposed, one is a more traditional approach such as adding network elements to increase sustainability in the WDS, and the other one is based on using the reclaimed water for non-potable water demand and fire flow. In this chapter, the main focus is on the identification of the current WDS problems with the current population and proposing alternatives to those problems using the scenario planning approach. Overall, the urban water system planning tool provides a fast overview for scenario evaluations. Switching between scenarios and visualizing the time steps for each scenario is faster and easier for the current population and water demand scenarios.

CHAPTER 7

SCENARIO EVALUATION: POPULATION CHANGE

In this chapter, population and water demand variations for the future WDS is investigated in order to analyze the effects on the technical and environmental sustainability of water networks. First, the population and water demand increase is tested on each of the current water system scenario. The base demands as well as pipe sizes in the water network are modified considering water demand and population increase assumptions. Second, sustainability of the WDS is evaluated based upon the assumption of water demand and population would decrease in the future.

7.1   Scenario evaluation: population increase

7.1.1   Scenario IV: baseline

Population and water demand in the example water network are increased in the baseline scenario. The total base demands at the nodes are approximately 443 GPM which was approximately 385 GPM in the current system scenario. Diameters of the water mains have decreased based on the average velocities at the pipes. Water demands at each node is increased and then the average velocities are calculated for the simulation time (i.e. hours between 96 and 119).

The WDS is modified based upon the average velocities of the pipes. If the velocities are lower than 0.15 m/s, then the size of pipe diameter is replaced with the smaller size. The main reason of reducing the pipe diameters is to analyze what would happen in the future if the current WDS had smaller size diameters. Traditionally, if the water demand and population increase in a WDS, additional network components such as storage tanks and\or pumping systems would be added to the

water network since it is more cost effective than replacing large number of water mains. Figure 7.1 shows the existing water network pipe diameters and the proposed changes in pipe diameters.
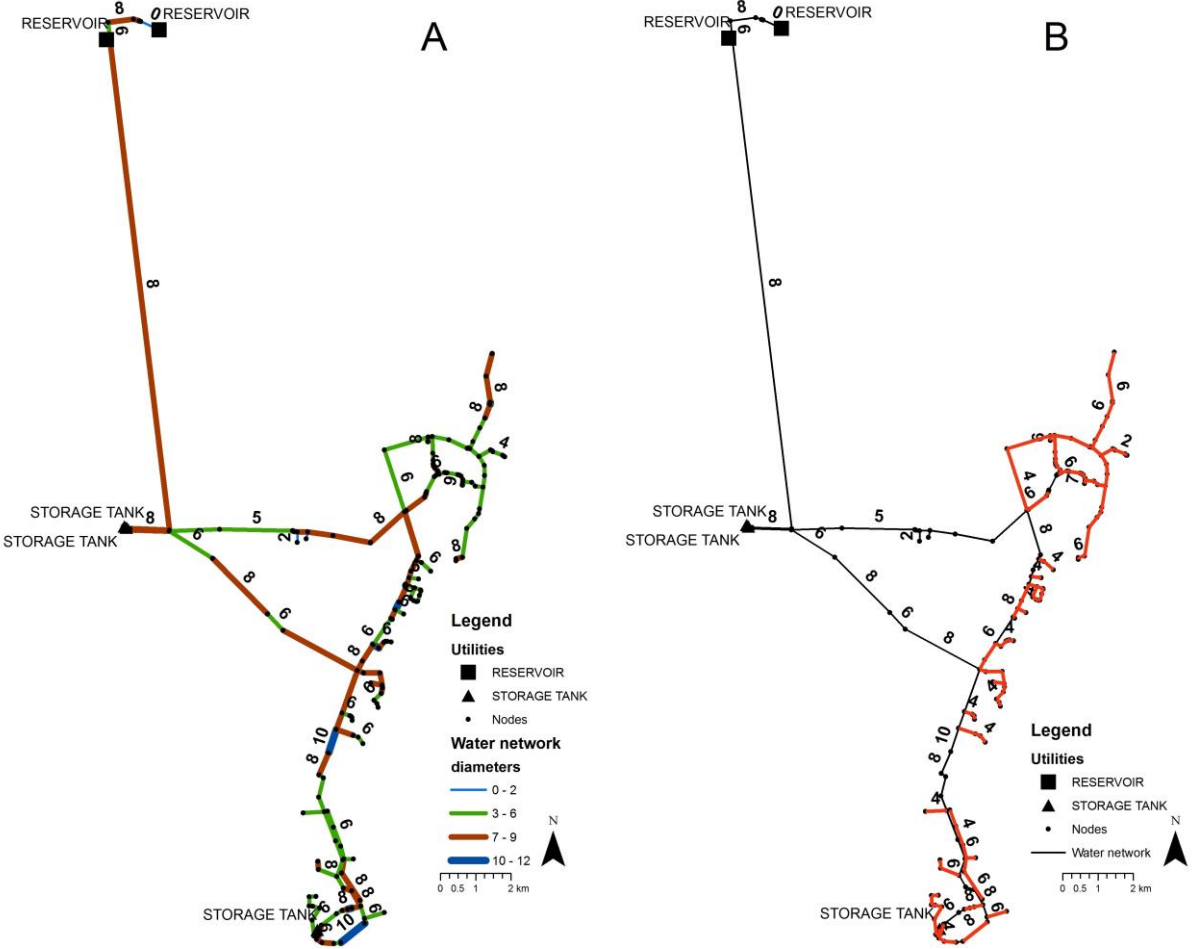
Figure 7.1 A. The existing water network pipe diameters. B. The proposed changes in pipe diameters in the baseline scenario.

The new network is analyzed to calculate the overall sustainability indices and technical sustainability of the WDS for each zone. The results of the technical sustainability assessment are given in Table 7.1.

The SI scores show that the increasing population and water demand deteriorate the pressure performance indices specifically at zones 4 and 5. The sustainability score of the nodal pressure parameter in Zone 5 in the current system scenario was 0.03 (see Table 6.2) which is decreased to 0 when there is an increased demand in the WDS. On the other hand, the sustainability scores for the water age parameter improved for all zones due to the decrease in pipe diameters.

Table 7.1 Technical sustainability assessment results for Scenario IV: baseline.

Zones	$SI_{pressure}$	$SI_{waterage}$	$SI_{overall}$
Zone 1	0.47	0.94	0.71
Zone 2	0	1	0.5
Zone 3	1	1	1
Zone 4	0.74	0.93	0.83
Zone 5	0	0.16	0.08
$SI_{network,k}$	0.44	0.81	

Results for the environmental sustainability score for energy intensity are given in Table 7.2. The energy intensity is calculated for the entire simulation time in the EPANET software. The total energy intensity for the baseline scenario is 2216.02 Kw-hr/Mgal.

Table 7.2 Energy intensity for Scenario IV: baseline.

Pumps	Energy Intensity Kw-hr/Mgal
111	1,095.3
114	1,211.95
Total	**2,307.25**

7.1.2   Scenario V: new pump

The population and water demand increase scenario is also applied to the new pump scenario alternative. Base demands at nodes and diameters of the pipes are modified. The total base demands at the nodes are approximately 443 GPM. In order to simulate the fire flow successfully, the network has to be modified again. The proposed network modifications for the current system scenario are not enough for the increased population and water demand scenario.

The flow increases in the network to meet the demand result in lower nodal pressures and even negative pressures at a few of the nodes. In order to eliminate the problem, another booster pump is included at the close proximity to the storage tank at Zone 2. Figure 7.2-A represents the Scenario II: new pump modifications which was introduced in the current system scenarios. Figure 7.2-B represents the Scenario V: new pump modifications in order to eliminate the negative pressure problems in EPANET software simulation for the future population and water demand increase assumptions. As can be seen in Figure 7.2-B, the proposed booster pump is located in Zone 2.
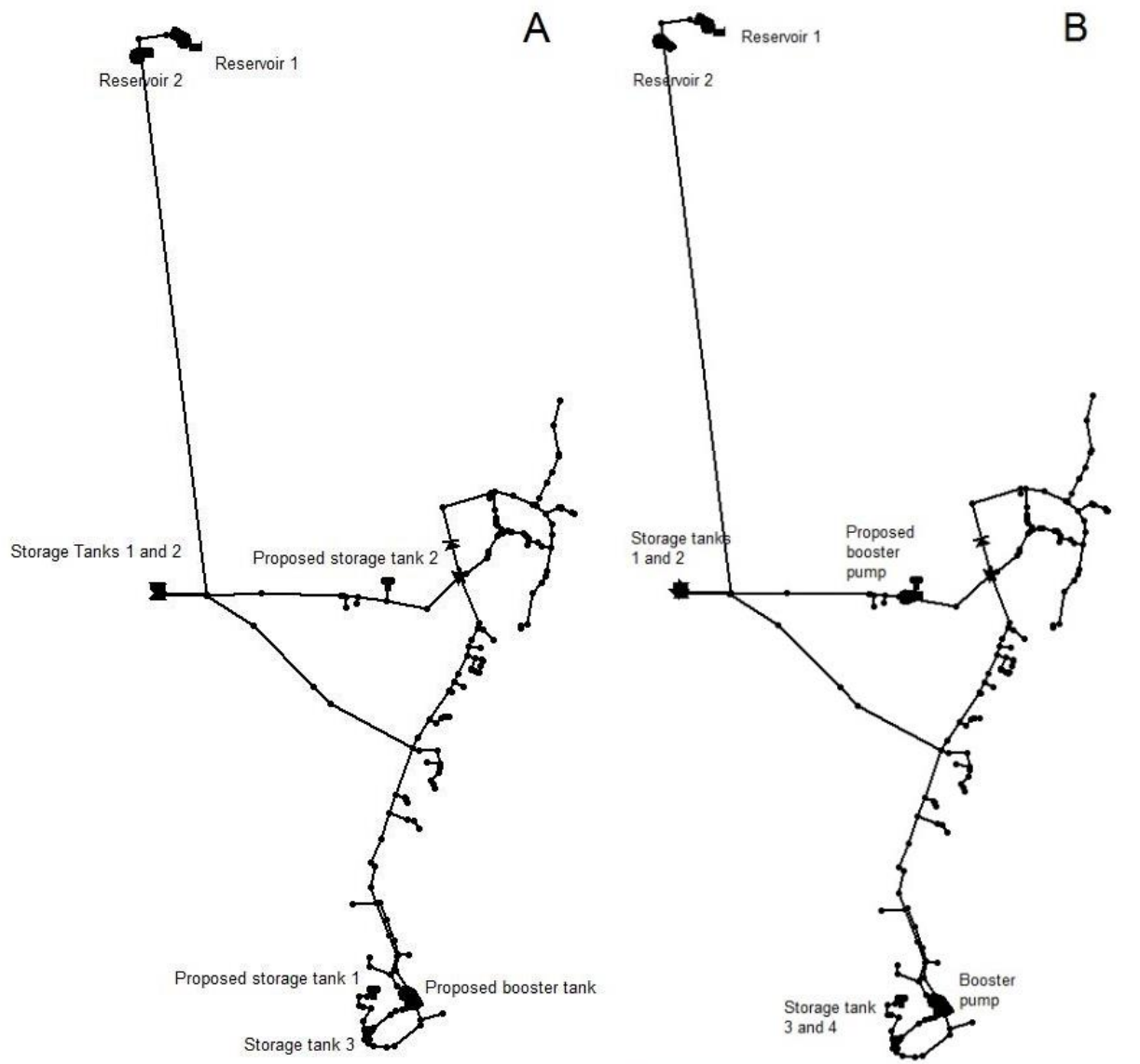
Figure 7.2 A. Scenario II: new pump B. Network modifications for Scenario V: new pump in the population increase alternative.

7.1.2.1 *Technical sustainability of Scenario V - new pump with increased demand condition*

Once the base demands increased in the new pump scenario, the EPS is first applied without the fire flow condition. Average velocities are calculated from time step 96 to 119 in order to determine the new pipe diameters in the water network. If the average velocity of the pipe is less than 0.15 m/s, the diameter of the corresponding pipe is decreased linearly to a smaller commercial size in order to analyze how the WDS would function if the current system had smaller pipe sizes. Figure 7.3 shows pipe diameters in the existing water network and the proposed changes in pipe diameters.
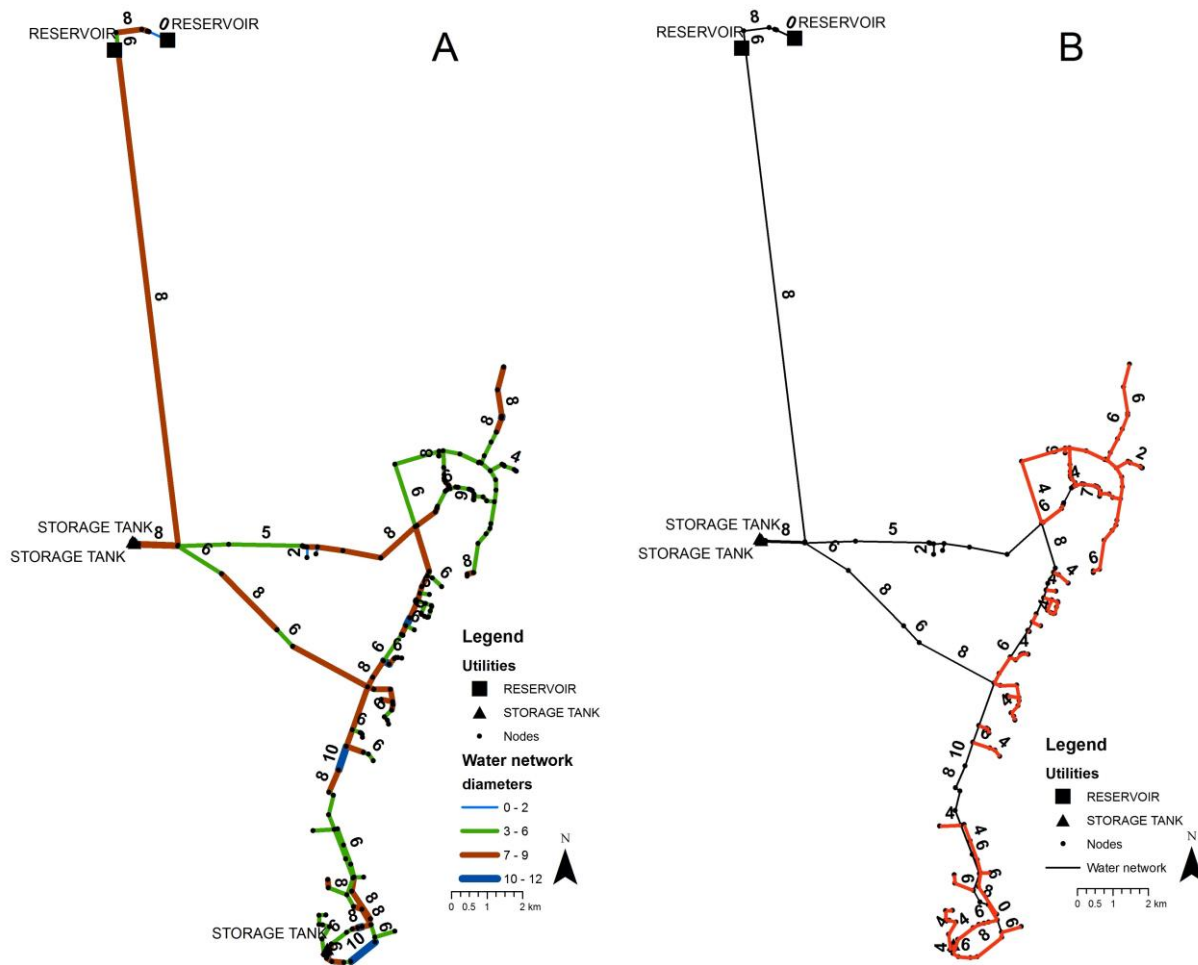
Figure 7.3 A. Pipe diameters in the existing water network. B. The proposed changes in pipe diameters in Scenario V: new pump.

After pipe diameters are modified, the EPS results from time step 96 to 119 are used to calculate the technical sustainability for the entire study area. Figure 7.4 illustrates the EPS results from time step 101 to 105 for nodal pressure parameter. The peak demand corresponds to time steps 102, 103, and 104. As seen in Figure 7.4, the nodal pressure performances of nodes corresponding to zones 1 and 3 are in the satisfactory state during the peak demand hours. However, the nodal pressure performances of nodes corresponding to Zone 2 are in the vulnerability state continuously.

The EPS for the water age parameter is visualized using the proposed visualization approach for the new pump scenario and is given in Figure 7.5. The water age parameter of nodes located in zones 1 and 3 are in the unsatisfactory state, which indicates vulnerability. One reason for the high water ages in these zones is the inflow from the proposed storage tank, which is located at Zone 2 (see Figure 7.2).

119
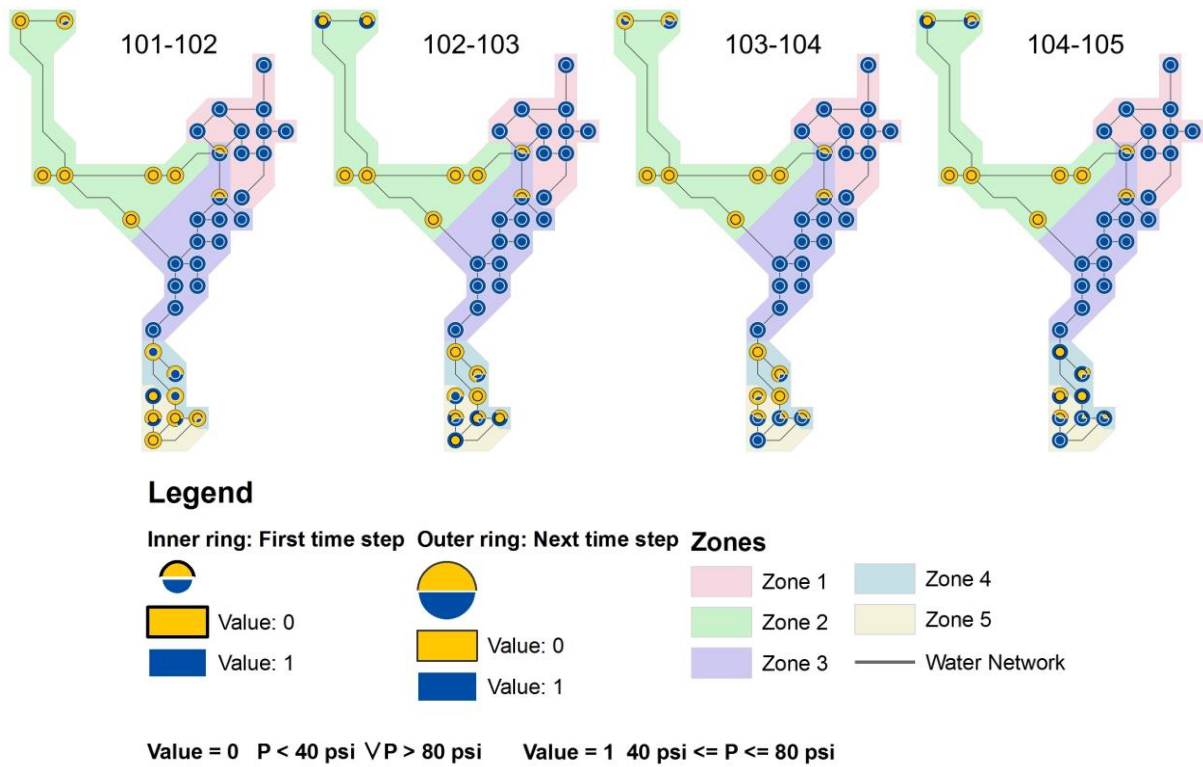
Figure 7.4 The EPS results for Scenario V: new pump with the increased population condition for the nodal pressure from time step 101 to 105.
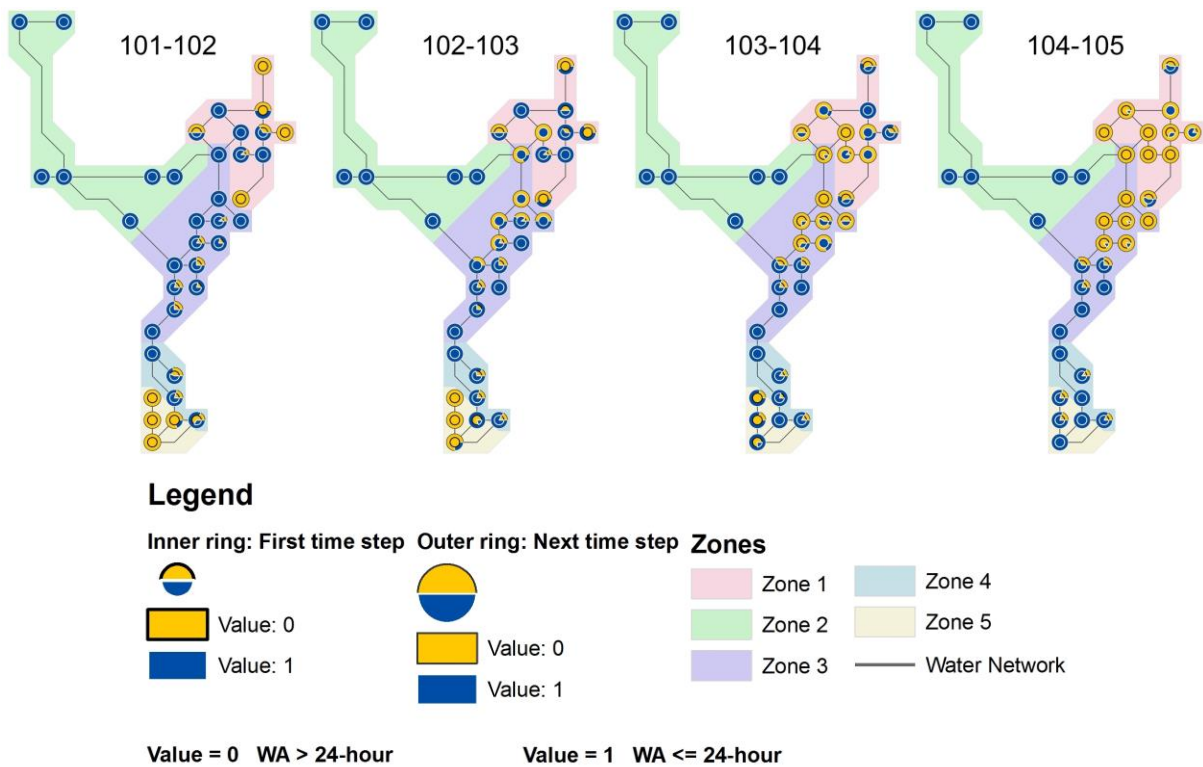
Figure 7.5 The EPS results for Scenario V: new pump in increased population condition for the water age from time step 101 to 105.

Reliability, resiliency and vulnerability performance criteria are calculated for the future water demand increase option of the new pump scenario using equations 4.3, 4.4, and 4.5, respectively. The technical sustainability assessment methodology is then applied to the new pump scenario without the fire flow condition. The results of the technical sustainability calculations for the nodal pressure and water age parameters (i.e. $SI_{network,pressure}$ and $SI_{network,waterage}$ respectively) are given in Table 7.3. The technical sustainability score of the new pump scenario for the nodal pressure parameter (i.e. $SI_{network,pressure}$) is 0.63 while for the water age parameter (i.e. $SI_{network,waterage}$) it is 0.57. In the current population and water demand scenario (i.e. Scenario II: new pump) the technical sustainability scores for the nodal pressure and water age parameters were 0.54 and 0.93, respectively (see Table 6.3). Although the technical sustainability of the network for water age parameter is higher than 0.5, scores for zones 1 and 5 are significantly lower than the rest of the zones.

Table 7.3 The technical sustainability results for Scenario V: new pump without fire flow.

Technical sustainability	$SI_{network,pressure}$	**0.63**	Zones	$SI_{pressure}$
			Zone 1	0.98
			Zone 2	0
			Zone 3	1.00
			Zone 4	0.55
			Zone 5	0.62
	$SI_{network,waterage}$	**0.57**	Zones	$SI_{waterage}$
			Zone 1	0.12
			Zone 2	1
			Zone 3	0.53
			Zone 4	0.89
			Zone 5	0.30

7.1.2.2 _Environmental sustainability of Scenario V - new pump_

In the new pump scenario, total fresh water consumption is approximately 443 GPM in the WDS assuming that the population will increase while the water consumption per person will decrease with the demand management activities such as using high efficient water appliances for indoor water consumption and outdoor irrigation (see Table 4.6 for the water demand management alternatives). The energy intensity has increased in the future new pump scenario by 34 %. In the current system, total energy intensity was 2429.48 Kw-hr/Mgal, which is now 3259.88 Kw-hr/Mgal. Energy intensity values of each pump together with total fresh water use for the new pump scenario are given in Table 7.4.

Table 7.4 Environmental sustainability scores for Scenario V: new pump without fire flow condition.

Total fresh water use (GPM)	443.11			
Total energy intensity (Kw-hr/Mgal)	3259.88	Energy intensity for each pump	**Pump**	**Energy intensity**
			111	1,069.88
			114	1,150.66
			136	248.18
			186	174.67
			159	616.49

7.1.2.3 *Scenario V- New pump with increased demand condition during fire flow*

The fire flow simulation is applied to the new pump scenario in order to investigate the sustainability of the water network when the population and water demand are increased in the future. ISO (2008) minimum fire flow regulations are applied to simulate fire flow in the water distribution network. The fire flow is simulated at the same location, which is located at Zone 5 (see Figure 6.7). A separate demand pattern is used at this node in order to simulate the fire flow. The demand coefficients are modified to meet the minimum fire flow regulations of 1,000 GPM for two hours (i.e. time steps 102 and 103). This demand pattern is assigned only to the node where the fire flow is simulated.

7.1.2.3.1 *Scenario V - New pump: The technical sustainability calculation the during fire flow*

Results of the fire flow simulation are visualized for the nodal pressure and water age parameters for the time step from 101 to 105 using the proposed visualization methodology. This approach enables easy comparison between the fire flow simulation and without fire flow simulation outcomes. Figures 7.6 and 7.7 demonstrate the changes in nodal pressures and water ages, respectively.

Similar to the technical sustainability assessment for the current system scenarios, the SI methodology is used to produce scores for the nodal pressure and water age parameters for each node and then aggregated into technical $SI_{network,pressure}$ and $SI_{network,waterage}$, respectively. Results showed that the fire flow simulation in the new pump scenario has significant impact on the SI score for nodal pressure parameter at zones 4 and 5. In addition, both under fire flow and without fire flow conditions, the water ages performances at Zone 1 are significantly low. This is due to the second storage tank (see Figure 7.2-A, the proposed storage tank 2), which provides water to zones 1 and 2 when there is a fire flow. Results of the technical sustainability assessment for the new pump scenario during fire flow are given in Table 7.5 (see Table 6.5 for the current population and water demand Scenario II: new pump).
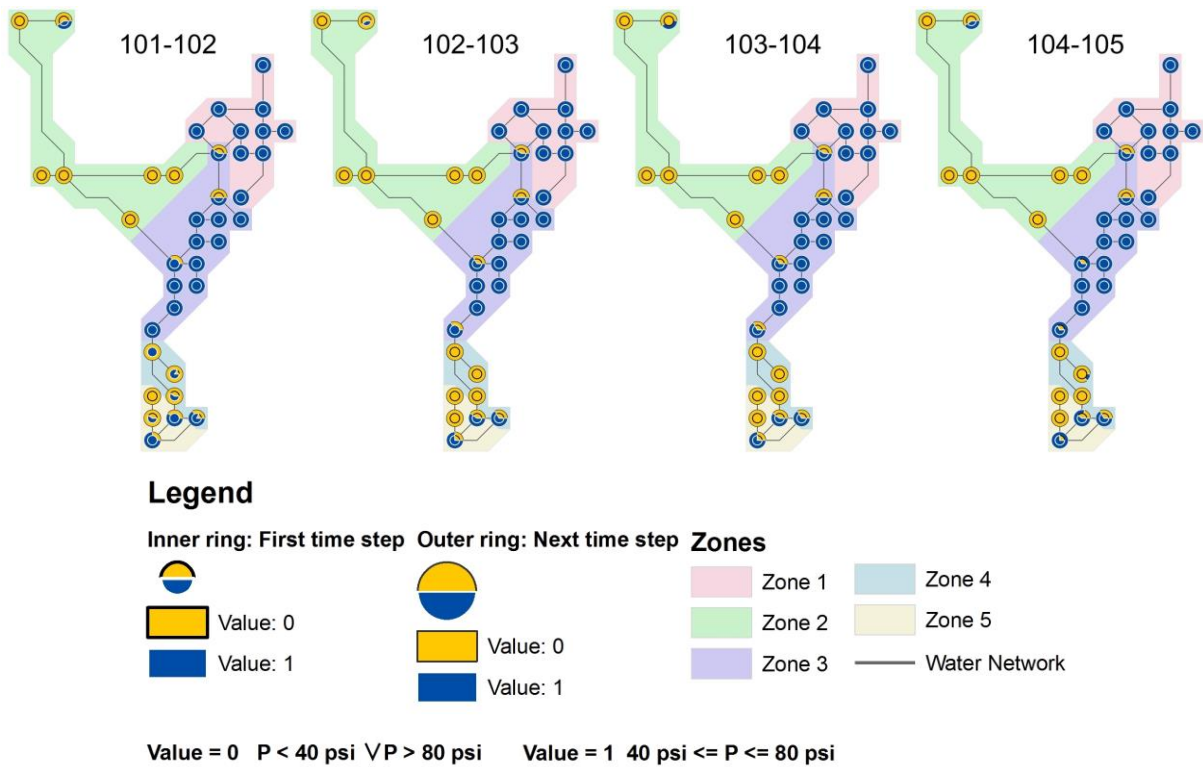
Figure 7.6 The EPS results for Scenario V: new pump during fire flow in increased population condition for the nodal pressure from time step 101 to 105.
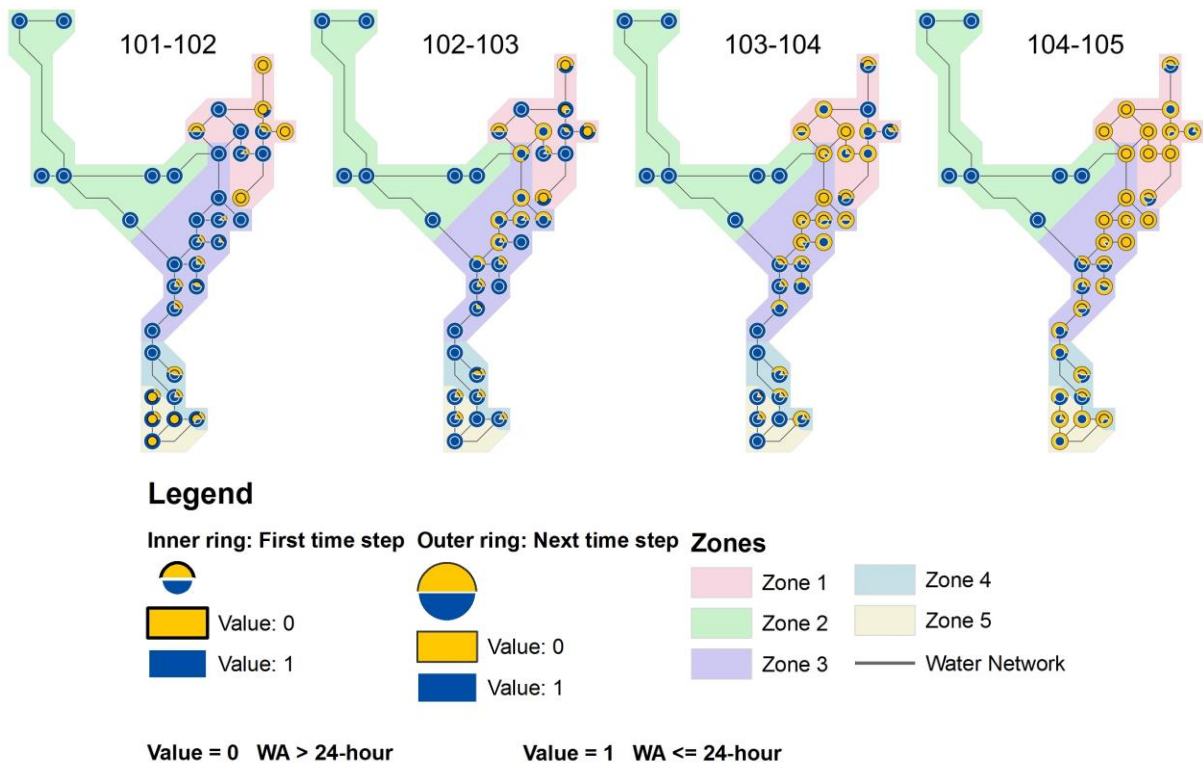
Figure 7.7 The EPS results for Scenario V: new pump during fire flow in increased population condition for the water age from time step 101 to 105.

Table 7.5 The technical sustainability results for Scenario V: new pump during fire flow.

Technical sustainability	SI$_{network,pressure}$	**0.51**	Zones	SI$_{pressure}$
			Zone 1	0.86
			Zone 2	0
			Zone 3	0.99
			Zone 4	0.25
			Zone 5	0.44
	SI$_{network,waterage}$	**0.51**	Zones	SI$_{waterage}$
			Zone 1	0.07
			Zone 2	1
			Zone 3	0.38
			Zone 4	0.73
			Zone 5	0.37

7.1.2.3.2   Scenario V - New pump: Environmental sustainability during fire flow

In the new pump scenario under fire flow condition, total fresh water consumption has not changed and it is approximately 443 GPM assuming that the population will increase while the water consumption per person will decrease with the demand management activities such as using high efficient water appliances for indoor water consumption and outdoor irrigation. Total energy intensity when there is a fire flow is 3229.38 Kw-hr/Mgal. Environmental sustainability scores for the new pump scenario during fire flow condition are given in Table 7.6.

Table 7.6 Environmental sustainability scores for Scenario V: new pump under fire flow condition.

Total fresh water use (GPM)	443.11			
Total energy intensity (Kw-hr/Mgal)	3229.38	Energy intensity for each pump	PUMP	Energy intensity
			111	1,068.89
			114	1,150.23
			136	247.21
			186	173.50
			159	589.55

7.1.3   Scenario VI - Reclaimed Water for Fire Flow

The feasibility and sustainability of reclaimed water for fire flow scenarios are investigated assuming that the population and water demand will increase linearly by 25 % in the future. In addition to the increase population and water demand assumption, the current water demand variations for the non-potable WDS are applied to the reclaimed scenario options. Based on the sub-scenario options in the current system evaluation, the dual WDS serves for the non-potable indoor and outdoor water demand as well as for the fire flow in Option A. The reclaimed water is used for only outdoor water demand and fire flow in Option B. While in Option C both the non-potable and potable water networks are used for the fire flow and for the non-potable indoor and outdoor water demand, in Option D the dual water network is only used for the outdoor water demand and both the potable and non-potable WDSs are used for the fire flow. Water demand assumptions for each scenario option are provided in Chapter 4, Table 4.3 based on the percentage changes.

7.1.3.1   *Scenario VI - Reclaimed water for fire flow: The technical sustainability calculation*

In order to calculate the technical sustainability scores, the same design layout and pipe sizes are used for the non-potable water network. On the other hand, pipe sizes for the potable water network in each scenario option are reduced based on the average velocities at the each pipe section (i.e. average velocities ≤ 0.15 m/s). After altering the pipe sizes as well as base demands in each scenario option, the technical sustainability assessment methodology is applied to the potable water network for each sub-scenario.

7.1.3.1.1 Scenario VI - Option A

Base demands at potable and non-potable water networks are modified in order to meet the future water demand. As mentioned before, the pipe diameters in the potable water network are decreased to the next smaller pipe sizes in order to analyze the future water demand and population changes if the existing water network had smaller pipe sizes.

Figure 7.8 illustrates the pipe diameters in the existing system and the proposed changes in the pipe diameters. In Figure 7.8-B, the modified pipes are marked in red. As can be seen from this figure, almost all pipes in zones 1, 4, 5 and the part of pipes Zone 3 are reduced in size. While none of the pipes in Zone 2 are modified since the velocities in the pipes in this zone was satisfactory (i.e. average velocities ≥ 0.15 m/s).

The fire flow is simulated at the non-potable water network and the fire flow is applied to the same node that was simulated in the current system evaluation. In addition to fire flow, the non-potable water network is used to meet the non-potable

indoor and outdoor water demand. The EPS results for the nodal pressure and water age parameters from time step 101 to 105 are illustrated in figures 7.9 and 7.10, respectively.
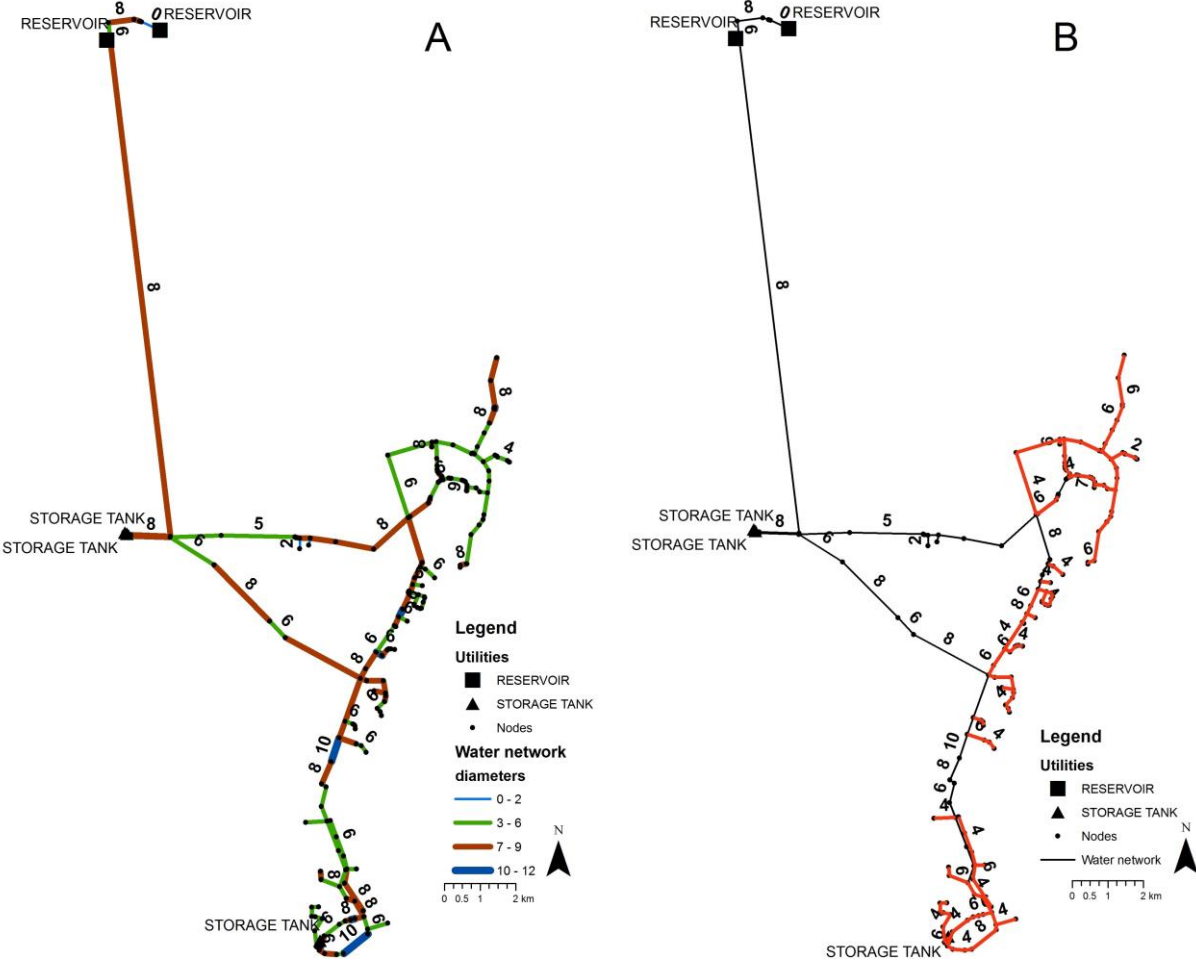
Figure 7.8 A. The pipe diameters of the existing system. B. The proposed changes in pipe diameters for Scenario VI Option A.

The $SI_{network,pressure}$ and $SI_{network,waterage}$ are calculated separately as well as $SI_{pressure}$ and $SI_{waterage}$ for each zone. The results are given in Table 7.7. Technical sustainability scores of the entire system for the reclaimed water for fire flow scenario VI: option A are 0.62 for the nodal pressure parameter and 0.90 for the water age parameter which were 0.51 for both parameters in Scenario V: new pump during fire flow condition. For the current population and water demand scenario III: option A, the technical sustainability scores in terms of the nodal pressure and water age parameters were 0.62 and 0.77, respectively (see Table 6.8). Although, the technical sustainability score in terms of the nodal pressure parameter seems to be the same, the $SI_{pressure}$ scores at each zone have changed. For example, in Scenario III: option A the $SI_{pressure}$ was 0.47 at Zone 1, while the $SI_{pressure}$ results for zones 4 and 5 were 0.61 and 0.71, respectively.
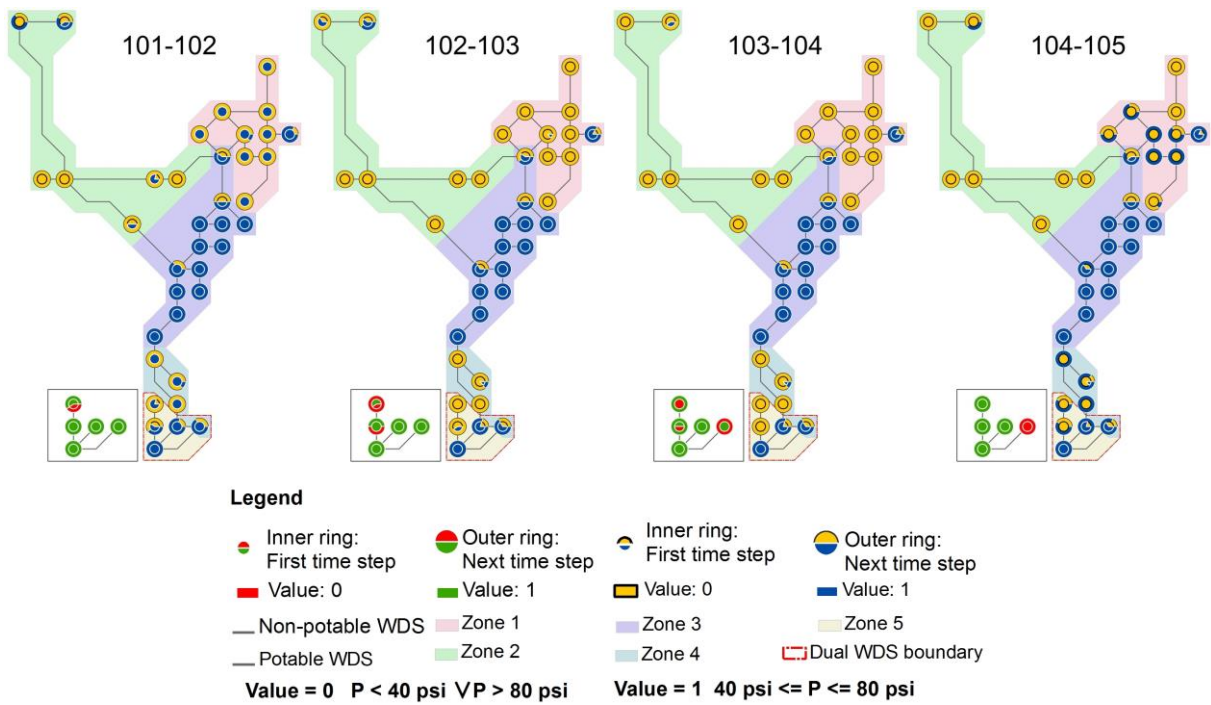
Figure 7.9 The EPS results for Scenario VI Option A during fire flow in increased population condition for the nodal pressure from time step 101 to 105.
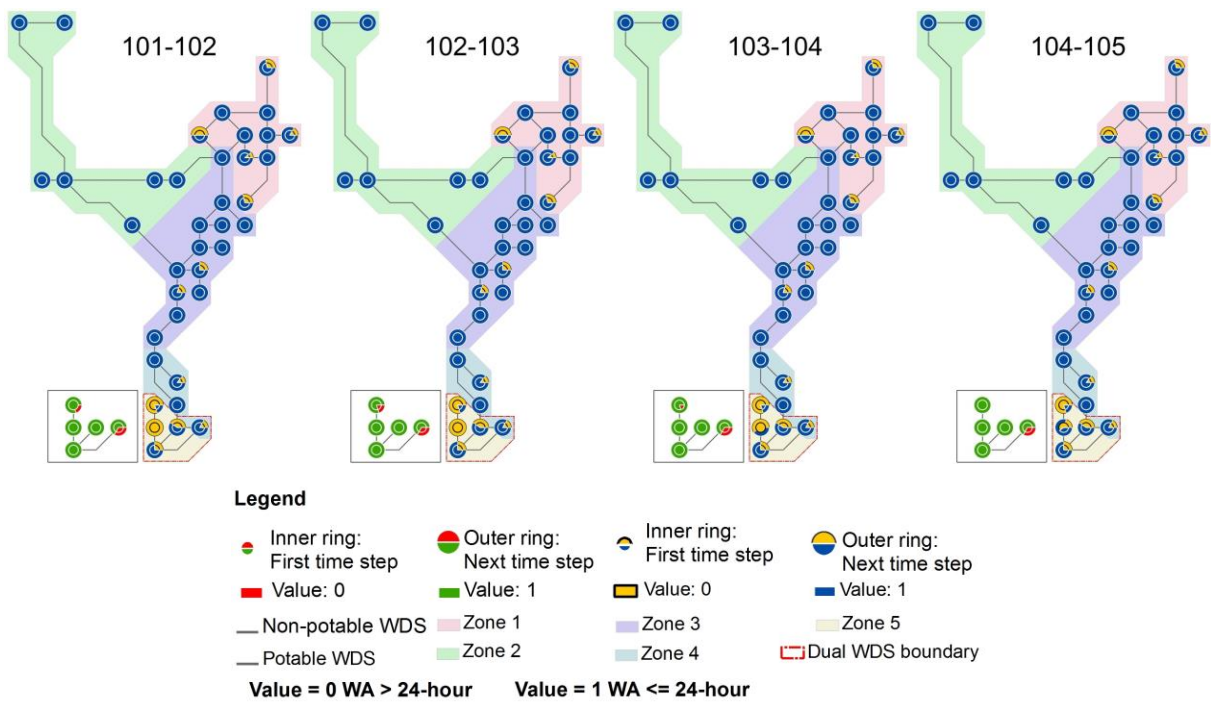
Figure 7.10 The EPS results for Scenario VI Option A during fire flow in increased population condition for the water age from time step 101 to 105.

Table 7.7 The technical sustainability calculation for Scenario VI: Option A in potable and non-potable WDSs.

Scenario	Zone	SI$_{pressure}$	SI$_{waterage}$
Scenario VI Option A	Zone 1	0.68	0.92
	Zone 2	0.08	1
	Zone 3	0.97	1
	Zone 4	0.52	1
	Zone 5	0.64	0.48
	Dual System	0.84	0.99
	SI$_{network,k}$	**0.62**	**0.90**

7.1.3.1.2   Scenario VI - Option B

In this scenario option, the non-potable water distribution network is planned to meet outdoor water demand and fire flow when there is an increase in population and water demand in the future. Similar to Scenario VI Option A, pipe diameters in the potable water network is modified based on the average velocities which are given in Figure 7.11 together with the existing system pipe diameters.
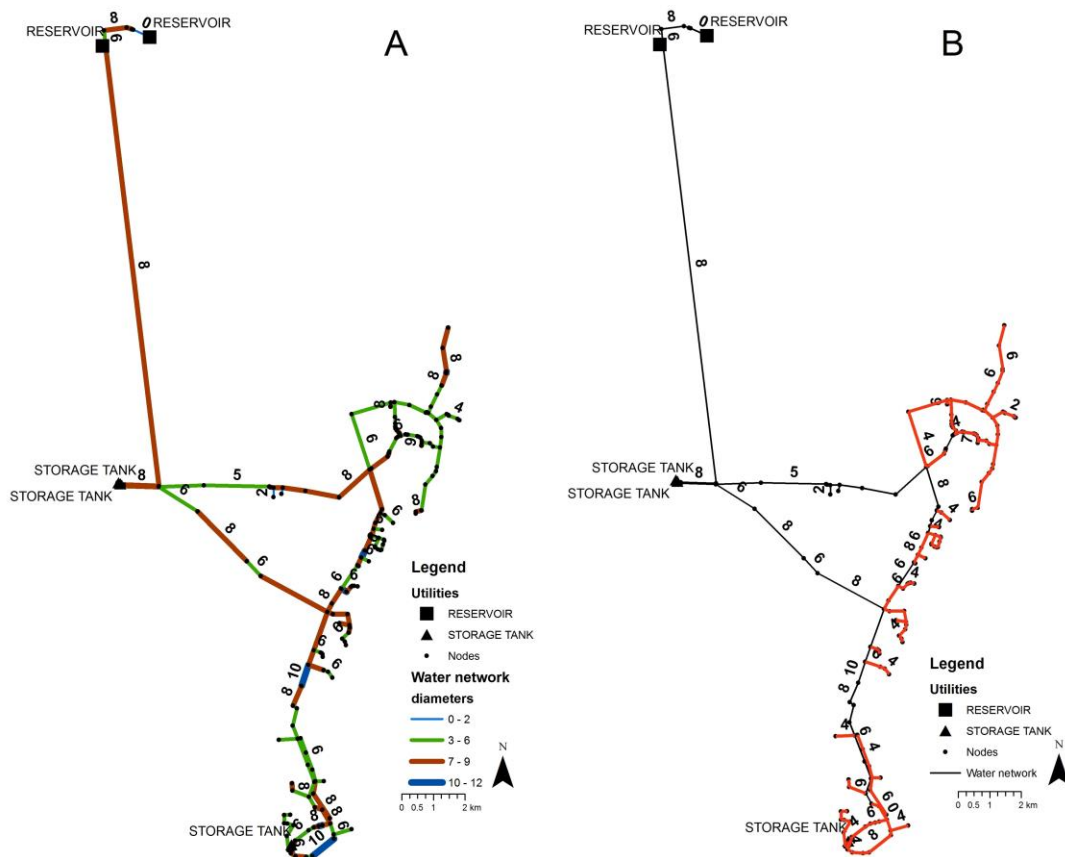
Figure 7.11 A. The pipe diameters in the existing system. B. The proposed changes in the pipe diameters in Scenario VI Option B.

The EPS is applied to both potable and non-potable water networks. Results from time step 101 to 105 for the nodal pressure and water age parameters are visualized in figures 7.12 and 7.13, respectively.
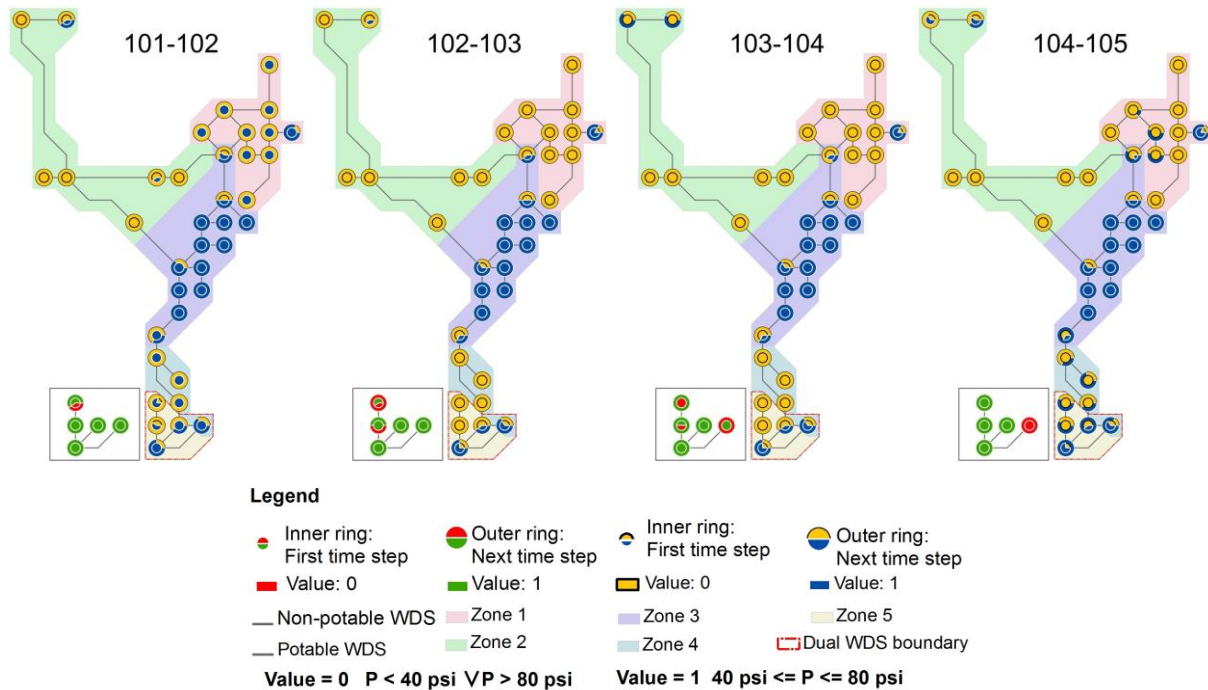
Figure 7.12 The EPS results for Scenario VI Option B during fire flow in increased population condition for the nodal pressure from time step 101 to 105.
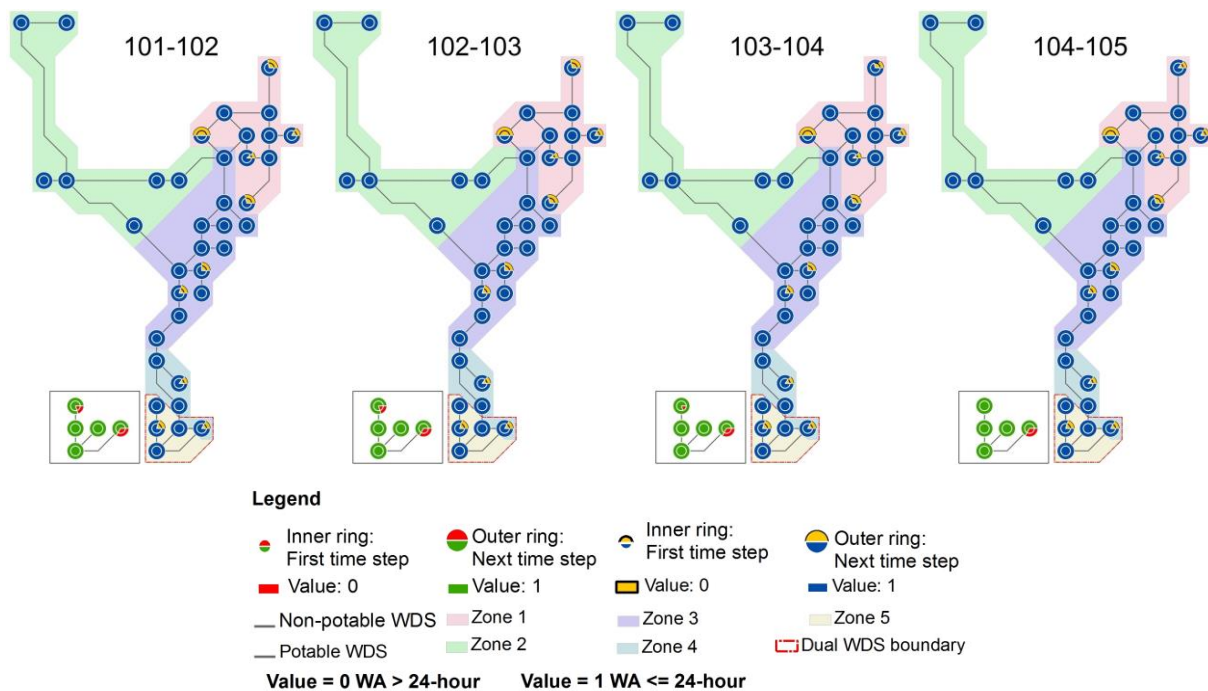
Figure 7.13 The EPS results for Scenario VI Option B during fire flow in increased population condition for the water age from time step 101 to 105.

In addition, the technical sustainability assessments for the entire network as well as the sustainability indices for each zone for the nodal pressure and water age parameters are given in Table 7.8. As can be seen from Figure 7.12, the nodal pressure performances at Zone 3 are continuously in the reliability state which is represented as "blue" circle views. On the other hand, the nodal pressure performances at zones 1, 2, and 4 have declined due to the increasing water demand.

In the current system scenario, the sustainability indices in terms of the nodal pressure parameter at zones 1, 2, and 4 were 0.42, 0.08, and 0.5, 1 respectively (see Table 6.9 for the current water demand scenario III Option B), while in the population and water demand increase assumption, the sustainability indices in terms of the nodal pressure at zones 1, 2, and 4 are 0.35, 0.08, 0.43, respectively. Figure 7.13 illustrates that the overall water age performance at the system improves continuously in the reliability state except some locations (i.e. dead-end nodes) when the population and water demand increases.

Table 7.8 The technical sustainability calculation for the Scenario VI Option B in potable and non-potable WDSs.

Scenario	Zone	$SI_{pressure}$	$SI_{waterage}$
Scenario VI Option B	Zone 1	0.35	0.93
	Zone 2	0.08	1
	Zone 3	0.96	1
	Zone 4	0.43	0.99
	Zone 5	0.53	1
	Dual System	0.82	0.98
	$SI_{network,k}$	**0.53**	**0.98**

7.1.3.1.3 Scenario VI - Option C

The Scenario VI: option C is proposed to assess the feasibility of using both potable and non-potable WDSs for fire flow considering the population and water demand will increase in the future. The non-potable water network is also used to meet non-potable indoor and outdoor water demands. The pipe diameters are modified in the potable water network and the proposed changes in the pipe diameters are given in Figure 7.14.

The fire flow is simulated at the same nodes and results of the EPS from time step 101 to 105 are given in figures 7.15 and 7.16 for the nodal pressure and water age parameters, respectively. The technical sustainability for the potable and non-potable water networks are calculated for Scenario VI: option C and given in Table 7.9.
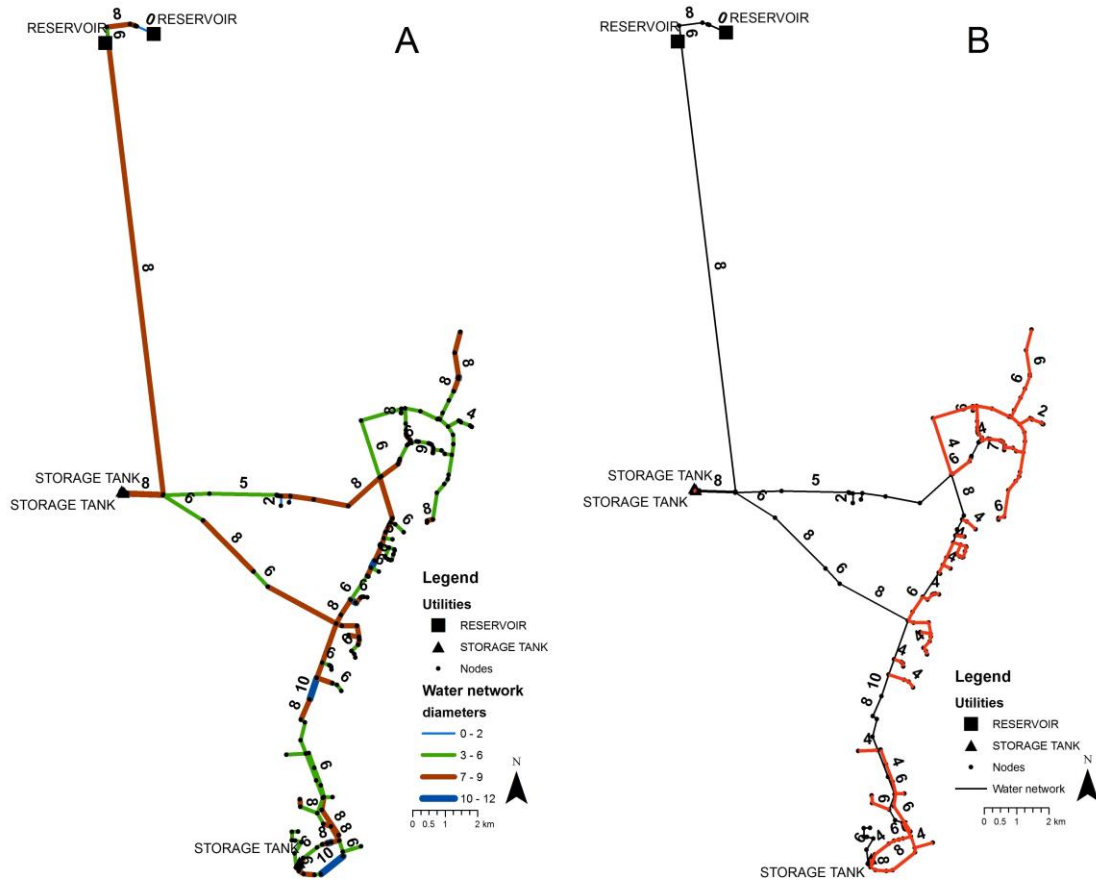
Figure 7.14 A. The pipe sizes for the existing WDS. B. The proposed changes in the pipe diameters for Scenario VI Option C.
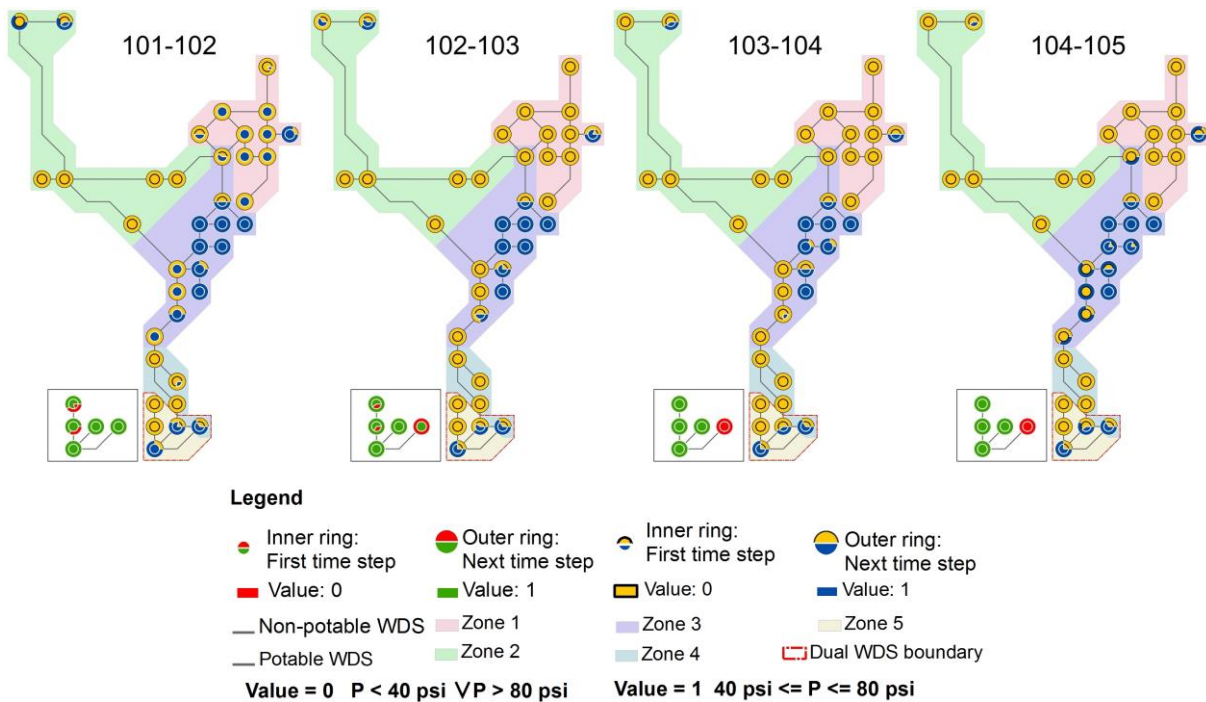
Figure 7.15 The EPS results for Scenario VI Option C during fire flow in increased population condition for the nodal pressure from time step 101 to 105.
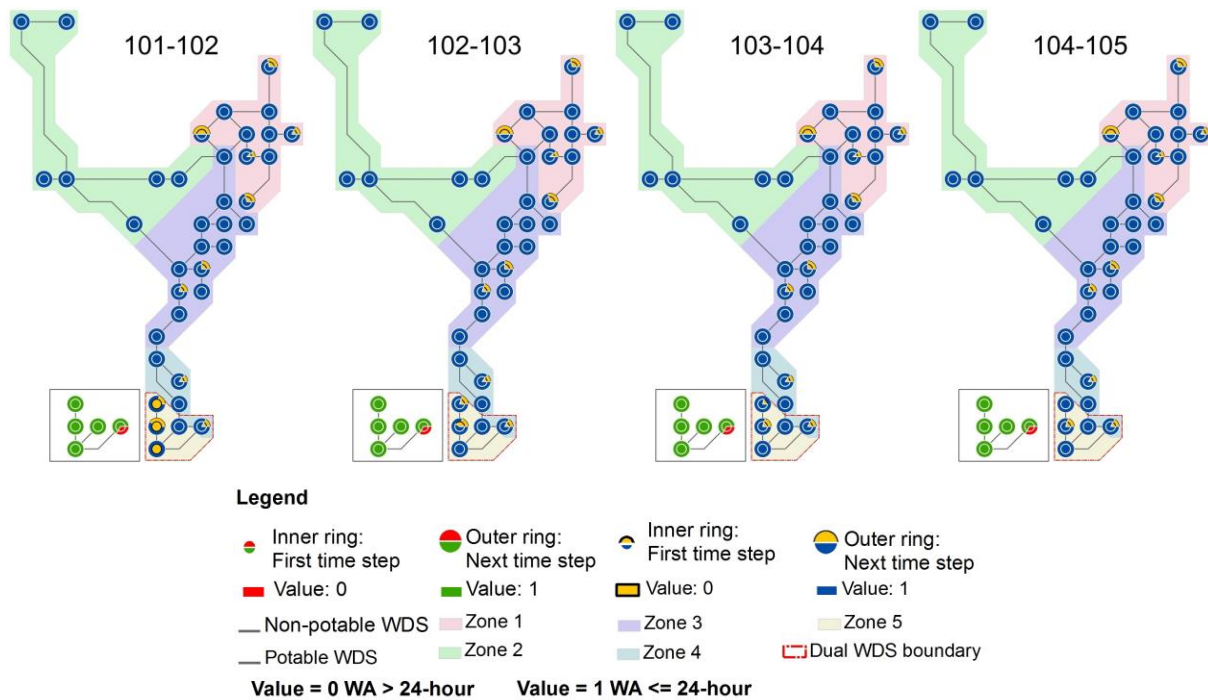
Figure 7.16 The EPS results for Scenario VI Option C during fire flow in increased population condition for the water age from time step 101 to 105.

Figure 7.15 illustrates that the fire flow has adverse impact on the nodal pressure performance at the overall WDS. The nodes at zones 1, 2, 4, 5, and the part of 3 are continuously in the unsatisfactory nodal pressure range. The technical sustainability score in terms of the nodal pressure and water age parameters are 0.49 and 0.91, respectively. For the current population and water demand Scenario III: option C, the technical sustainability score in terms of the nodal pressure and water age were 0.54 and 0.82, respectively (see Table 6.10).

Table 7.9 The technical sustainability calculation for Scenario VI Option C in potable and non-potable WDSs.

Scenario	Zone	$SI_{pressure}$	$SI_{waterage}$
Scenario VI Option C	Zone 1	0.34	0.92
	Zone 2	0.07	1
	Zone 3	0.87	1
	Zone 4	0.37	1.00
	Zone 5	0.41	0.58
	Dual System	0.85	0.99
	$SI_{network,k}$	**0.49**	**0.91**

7.1.3.1.4 Scenario VI - Option D

The base demands at the potable and non-potable WDSs are modified considering the future water demand increase assumptions. In this scenario, the fire flow is met using both dual and potable water networks while the dual WDS is also used for outdoor water demand. The sizes of pipes in the potable WDS are modified and the proposed changes in the pipe diameters are given in Figure 7.17 in order to analyze if the existing water network had smaller pipe sizes.
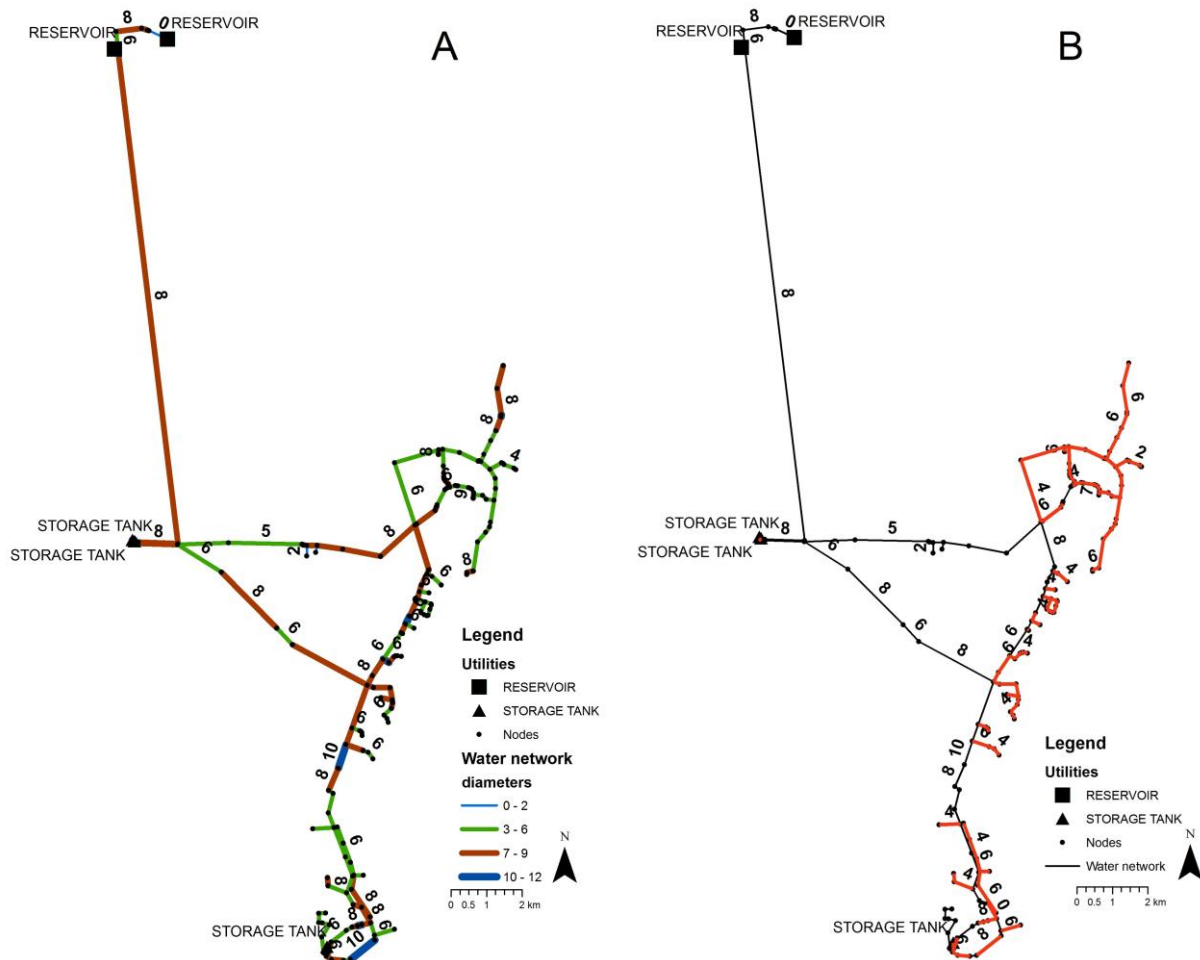
Figure 7.17 A. The pipe sizes for the existing WDS. B. The proposed changes in the pipe diameters for Scenario VI Option D.

After the EPS using the EPANET are completed, results for time steps between 101 and 105 are visualized for nodal pressure and water age parameters separately and given in figure 7.18 and 7.19, respectively. The technical sustainability scores are calculated for the entire potable and non-potable water networks. For the nodal pressure parameter, the technical sustainability score is 0.48 and for the water age parameter, it is 0.98. Sustainability scores for each zone with respect to nodal pressure and water age parameters are given in Table 7.10.

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The $SI_{network,pressure}$ and $SI_{network,waterage}$ are 0.48 and 0.98 in scenario VI: option D, respectively, while in Scenario III: option D (i.e. the current population and water demand scenario) the technical sustainability indices in terms of the nodal pressure and water age parameters were 0.50 and 0.90, respectively.
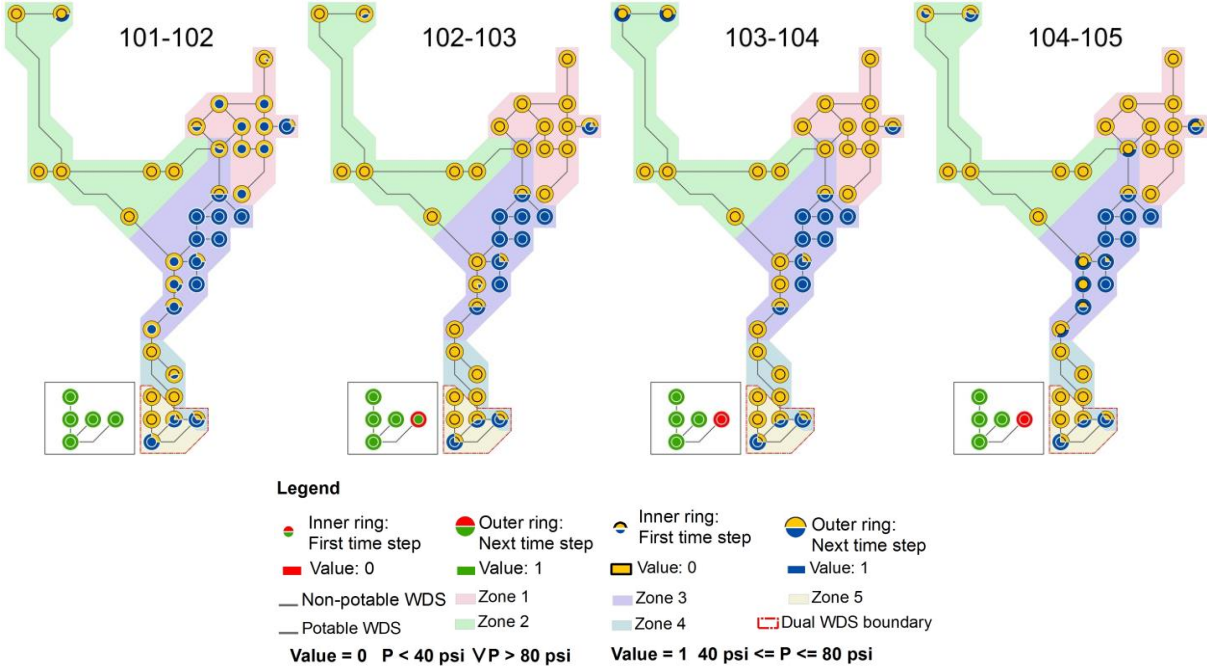
Figure 7.18 The EPS results for Scenario VI - Option D during fire flow in increased population condition for the nodal pressure from time step 101 to 105.
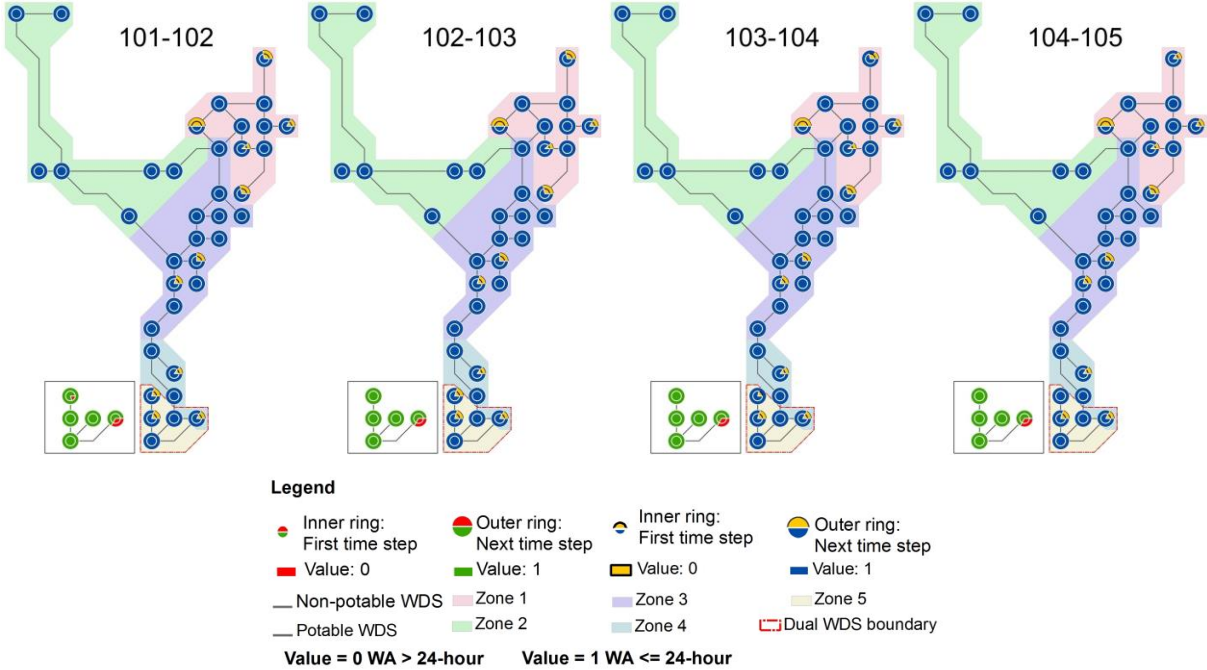
Figure 7.19 The EPS results for Scenario VI - Option D during fire flow in increased population condition for the water age from time step 101 to 105.

Table 7.10 The technical sustainability calculation for Scenario VI Option D in potable and non-potable WDSs.

Scenario	Zone	$SI_{pressure}$	$SI_{waterage}$
Scenario VI Option D	Zone 1	0.29	0.93
	Zone 2	0.07	1
	Zone 3	0.88	1
	Zone 4	0.27	0.99
	Zone 5	0.48	0.99
	Dual System	0.88	0.98
	$SI_{network,k}$	**0.48**	**0.98**

7.1.3.2 Scenario VI - reclaimed water for fire flow: The environmental sustainability calculation

Environmental sustainability criteria identified for the current water system evaluation are considered for the future water demand and population scenarios as well. Energy intensities of all the scenario options are retrieved from energy reports, which are provided by the EPANET software, EPS. Detailed information of each reclaimed water for fire flow sub-scenario is provided in Table 7.11.

Overall, total energy intensities in each scenario option have increased in comparison to the current system scenarios. This is because of the overall increase of flows in both potable and non-potable WDSs. Note that energy intensities might be reduced by optimizing pump schedules and curves, which is neglected in this dissertation.

Total fresh water use of each scenario option is given in Table 7.11. In scenario options A and C, 75 % of the base demands at zone 5 and the part of zone 4 is met with reclaimed water while in scenario options B and D 30 % of the base demands at the same location is met using the dual WDS.

Table 7.11 The environmental sustainability results for the scenario the reclaimed water for fire flow scenario options.

Scenario	Total fresh water use (GPM) (equivalent liter/s)	Total energy intensity (Kw-hr/Kgal)
Option A	396.02 (24.98)	3,278.38
Option B	424.43 (26.78)	3,316.66
Option C	396.02 (24.98)	3,353.3
Option D	424.43 (26.78)	3,359.75

7.2 Scenario evaluation: population decrease

7.2.1 Scenario VII: baseline

The assumption of decreasing population and water demand assumption is applied to the baseline scenario by reducing the total base demands at the nodes by 10 %. The total base demands in this option are approximately 347 GPM. The average velocities of the pipes are calculated at time steps between 96 and 119. Then, similar to the population increase assumption, the WDS is modified based upon the average velocities of the pipes. The pipes with velocities lower than 0.15 m\s are reduced in size with the smaller sizes. Figure 7.20 shows the existing water network pipe diameters and the proposed changes in pipe diameters.
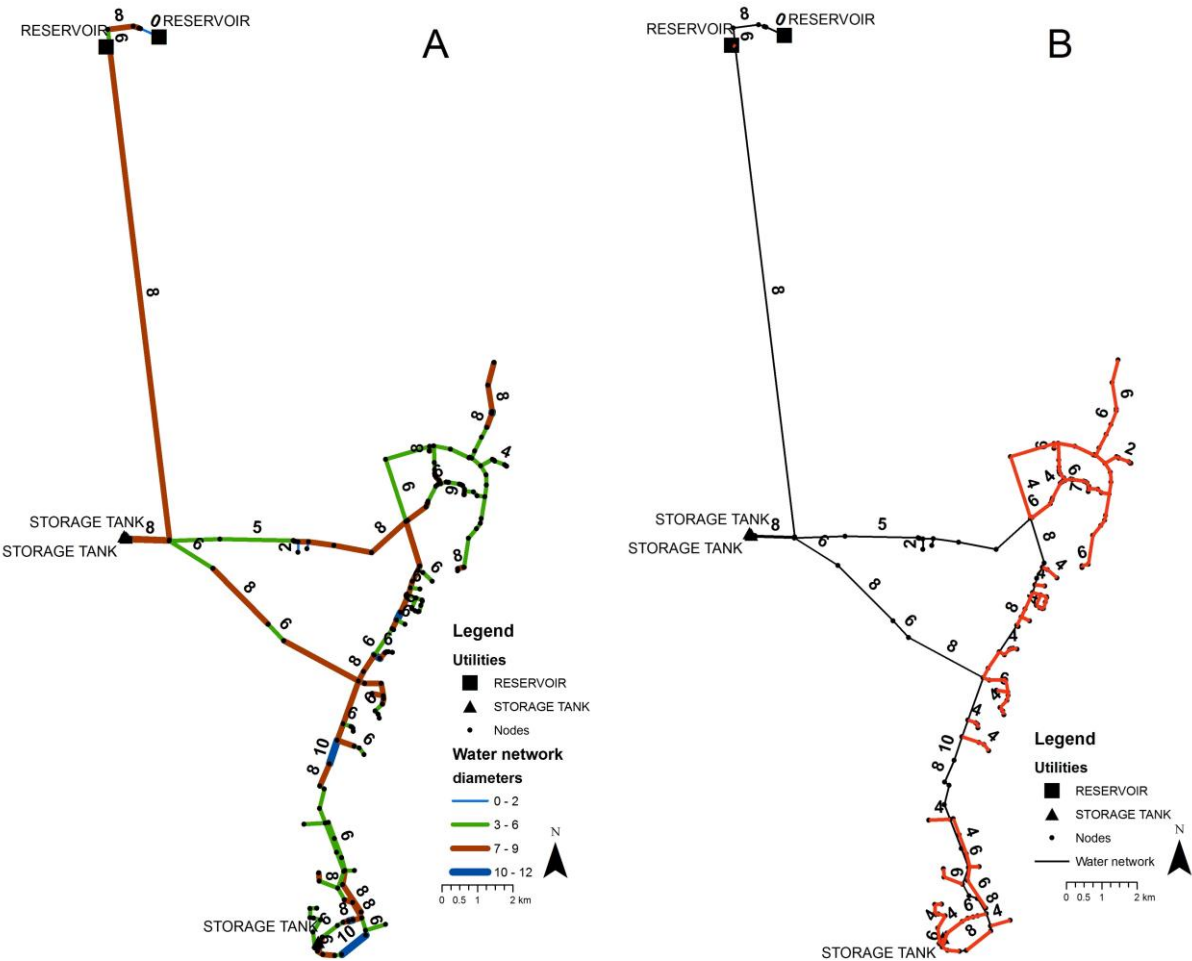
Figure 7.20 A. Pipe diameters in the existing water network. B. The proposed changes in pipe diameters in the baseline scenario.

The WDS is analyzed using the EPS function in the EPANET software in order to evaluate the sustainability indices for each zone and the technical sustainability for the entire network. The results of the technical sustainability assessment are given in Table 7.12. As oppose to the population increase scenario result, population decrease

condition results in increasing overall SI specifically in Zone 5. In the current system, the overall SI in Zone 5 was 0.07 that increased to 0.19. The energy intensity is calculated for the entire simulation time using the EPANET software. There are two main pumps in the baseline scenario located at the close proximity of two main reservoirs in order to provide water to the demand points. The total energy intensity for the baseline scenario is 2123.67 Kw-hr/Mgal.

Table 7.12 The technical sustainability results for scenario VII: baseline.

Zones	SI$_{pressure}$	SI$_{waterage}$	SI$_{overall}$
1	0.55	0.87	0.71
2	0.02	1	0.51
3	1	1	1
4	1.00	0.94	0.97
5	0.19	0.19	0.19
SI$_{network,k}$	0.55	0.80	

7.2.2 Scenario VIII: new pump

In this scenario, the population and water demand are decreased to approximately 347 GPM in the entire water network. After the base demands are modified in the new pump scenario for the decreased population and water demand assumption, average velocities of the pipes are calculated from time step 96 to 119 and the results are used to determine the pipes that need to be reduced in size. Figure 7.21 shows pipe diameters in the existing water network and the proposed changes in pipe diameters for the new pump scenario. The EPS is applied to the modified water network in order to calculate technical sustainability without fire flow and under fire flow condition. The fire flow is simulated at the same node which is located in Zone 5. The results of the technical sustainability calculations for the nodal pressure and water age parameters are given in Table 7.13.

Without the fire flow condition, the nodal pressure and water age parameters, specifically in Zone 5, have increased significantly comparing to the population increase option (see Table 7.3). The SI$_{pressure}$ and SI$_{waterage}$ scores were 0.62 and 0.30 for the new pump scenario without fire flow when the population and water demands are increased in the entire network. On the other hand, when there is a fire flow in Zone 5, the technical sustainability for the nodal pressure parameter decreases significantly (i.e. 0.42) (see Table 7.5 for the technical sustainability score results for the new pump scenario with increased water demands during fire flow). The total energy intensities for this scenario option without fire flow and during fire flow are 2,372.58 Kw-hr/Mgal and 2,397.9 Kw-hr/Mgal, respectively.
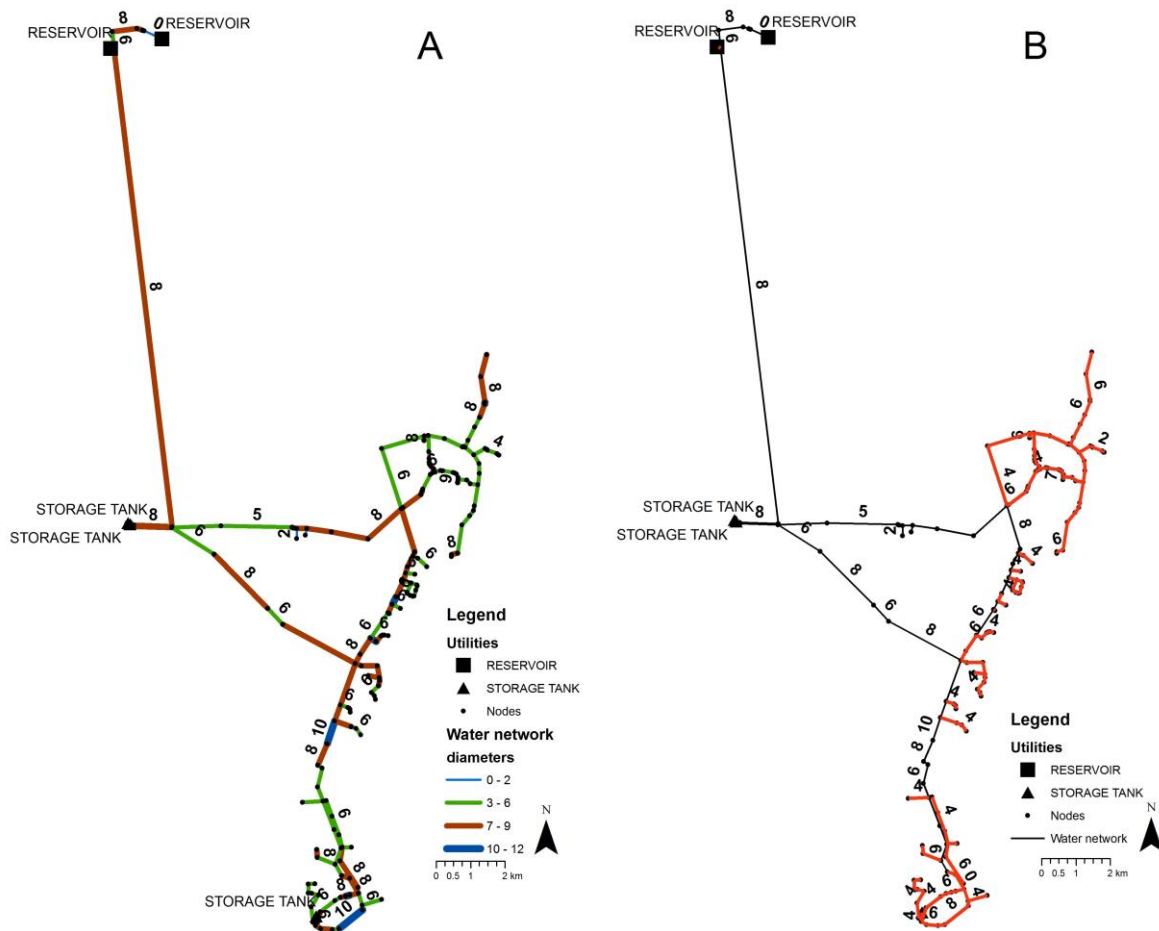
Figure 7.21 A. Pipe diameters in the existing water network. B. The proposed changes in pipe diameters in the new pump scenario.

Table 7.13 The technical sustainability results for the new pump scenario without fire flow and during fire flow condition.

Zones	UNDER FIRE FLOW		WITHOUT FIRE FLOW	
	$SI_{pressure}$	$SI_{waterage}$	$SI_{pressure}$	$SI_{waterage}$
Zone 1	0.36	0.80	0.60	0.80
Zone 2	0	1	0	1
Zone 3	0.96	1.00	1.00	0.99
Zone 4	0.29	0.99	0.67	0.99
Zone 5	0.42	0.99	0.73	0.93
$SI_{network,k}$	0.41	0.96	0.60	0.94

7.2.3 Scenario IX: reclaimed water for fire flow

Base demands at the potable and non-potable WDSs are reduced in this scenario option. The water demand variation between potable and non-potable water networks are explained in detailed in Chapter 4, Table 4.3. Basically, Options A and B are based on using the non-potable water network for fire flow and non-potable water demands while Options C and D concern using both potable and non-potable water networks for fire flow and meeting the non-potable indoor and\or outdoor water demand using the dual WDS.

For each sub-scenario, average velocities of the pipes are calculated for the simulation time steps from 96 to 119 only at the potable water network. If the average velocity of the pipe at each sub-scenario is lower than 0.15 m\s, pipe diameters are reduced linearly to the smaller commercial sizes. Once the potable water network modifications are completed, EPSs are applied to the potable and non-potable WDSs. The technical sustainability scores are calculated under fire flow conditions for each of the sub-scenario. The results are provided in Table 7.14 together with the environmental sustainability criteria (i.e. total fresh water use, energy intensity).

The technical sustainability scores for the current water system scenarios are given in Tables 6.8, 6.9, 6.10, and 6.11 for scenario options A, B, C, and D, respectively. The result of environmental sustainability criteria for the current water system scenarios is provided in Table 6.12. In Option A, 75 % of the base demands located in Zone 5 and the part of Zone 4 in the potable water network are met using the non-potable WDS. As seen in Table 7.14, when the population and water demands are decreased in the potable WDS, water ages in Zone 5 in Option A further deteriorates (see Table 6.7). On the other hand, decreasing water demand improves the nodal pressure sustainability indices in all of the reclaimed water for fire flow sub-scenarios.

Table 7.14 The technical sustainability scores together with the environmental sustainability criteria for each reclaimed water for fire flow sub-scenario.

Scenario	Zone	$SI_{pressure}$	$SI_{waterage}$	Total Fresh water use (GPM)	Energy intensity (Kw-hr/Kgal)
Option A	Zone 1	0.75	0.79	**309.9**	**3,007.05**
	Zone 2	0.10	1		
	Zone 3	1	1.00		
	Zone 4	0.91	0.99		
	Zone 5	0.84	0.06		
	Dual System	0.84	0.99		
	$SI_{network,k}$	**0.74**	**0.80**		

Table 7.14 Cont'd

Option B	Zone 1	0.66	0.85	**332.2**	**3,166.6**
	Zone 2	0.09	1		
	Zone 3	1.00	1		
	Zone 4	0.73	0.99		
	Zone 5	0.71	0.78		
	Dual System	0.82	0.98		
	SI$_{network,k}$	**0.67**	**0.93**		
Option C	Zone 1	0.53	0.64	**309.9**	**3,164.79**
	Zone 2	0.09	0.99		
	Zone 3	0.97	0.97		
	Zone 4	0.49	0.97		
	Zone 5	0.58	0.31		
	Dual System	0.88	0.99		
	SI$_{network,k}$	**0.59**	**0.81**		
Option D	Zone 1	0.46	0.87	**332.2**	**3,184.54**
	Zone 2	0.08	1		
	Zone 3	0.98	1		
	Zone 4	0.44	0.99		
	Zone 5	0.53	0.78		
	Dual System	0.88	0.98		
	SI$_{network,k}$	**0.56**	**0.94**		

7.3 Scenario Comparison: Population Increase and Decrease Scenarios

7.3.1 Multi-criteria decision analysis for the future population scenario assumptions

In order to analyze the feasibility of population and water demand increase and decrease scenarios with respect to the identified technical and environmental sustainability criteria, the same procedure, which was used to compare current WDS scenarios, is applied. The simple additive weighting aggregation method is used to conduct the MCDA. First, the scores of the technical and environmental sustainability criteria are normalized using a linear scale transformation methodology. Then, weights are calculated using the "rank sum" algorithms. The same ranked orders for environmental and technical criteria are used for comparing the future population increase and decrease scenarios (see Table 4.7).

7.3.2 Normalization of each criterion

In order to compare each scenario under population and water demand increase and decrease assumptions, scores of the technical and environmental criteria need to be normalized. The technical sustainability scores are normalized using the "benefit criterion" given in equation 4.16 while environmental sustainability criteria are normalized using the "cost criterion" which is provided in equation 4.17. Tables 7.15 and 7.16 show the raw data together with the normalized scores for the technical and environmental sustainability criteria for the population increase and decrease assumptions, respectively.

Table 7.15 Raw data and normalized scores for the technical and environmental sustainability criteria for the population and water demand increase scenarios.

	Scenarios during fire flow	Technical sustainability		Environmental sustainability	
		$SI_{network,pressure}$	$SI_{network,waterage}$	Total freshwater use (GPM)	Energy intensity (Kw-hr/mgal)
Raw values	New Pump	0.51	0.51	443.11	3,229.38
	Option A	0.62	0.90	396.0169	3,278.38
	Option B	0.53	0.98	424.4315	3,316.66
	Option C	0.49	0.91	396.0169	3,353.3
	Option D	0.48	0.98	424.4315	3,359.75
Normalized	New Pump	0.23	0	0	1
	Option A	1	0.82	1	0.62
	Option B	0.37	1	0.40	0.33
	Option C	0.06	0.85	1	0.05
	Option D	0	1.00	0.40	0

In Table 7.15, each criterion is normalized for all scenarios. Due to the normalization, for each criterion, one scenario is assigned a value of "0" and one scenario is assigned a value of "1". For example, the "new pump" scenario has the value of "0" for the total fresh water use criterion. This means that the "new pump" scenario has the lowest score in terms of total fresh water use criterion among all the scenario alternatives. On the other hand, Scenario III options A and C get the value of "1" since the maximum amount of reclaimed water is used in these scenario options. Total fresh water use and energy intensity criteria are normalized using the "cost criterion" procedure (i.e. equation 4.17). Therefore, the highest score is given to the lowest raw value while the $SI_{network,pressure}$ and $SI_{network,waterage}$ criteria are normalized

using "benefit criterion" procedure (i.e. highest score is given to the highest raw value).

Table 7.16 Raw data and normalized scores for the technical and environmental sustainability criteria for the population and water demand decrease scenarios.

	Scenarios during fire flow	Technical sustainability		Environmental sustainability	
		$SI_{network,pressure}$	$SI_{network,waterage}$	Energy intensity (Kw-hr/mgal)	Total freshwater use (GPM)
Raw Values	New Pump	0.41	0.96	2,397.9	346.78
	Option A	0.74	0.80	3,142.73	309.90
	Option B	0.67	0.93	3,166.6	332.17
	Option C	0.59	0.81	3,164.79	309.90
	Option D	0.56	0.94	3,184.54	332.17
Normalized	New Pump	0	1	1	0
	Option A	1	0	0.05	1
	Option B	0.79	0.86	0.98	0.40
	Option C	0.55	0.05	0.97	1
	Option D	0.46	0.88	0	0.40

7.3.3 Defining weights for each criterion

There are four ranking options that are considered in this dissertation in order to compare future population and water demand assumptions. Each ranking option is proposed to prioritize one criterion at a time. The "rank sum" algorithm is explained in detail in Chapter 4 section 4.5.3. Equation 4.18 is used to calculate the weights for each ranking option. Table 4.7 provides the ranked orders of each technical and environmental sustainability criteria. Calculated weights for each criterion are also given in Table 4.8.

7.3.4 Simple additive weighting methodology

Once the identified weights are assigned to each criterion, final scores are calculated for future population and water demand increase and decrease assumptions using Equation 4.19 in Chapter 4, section 4.5.4. This means that total scores will vary at each ranking option for population increase and decrease assumptions which enable comparing the scenarios under diverse priorities. Total scores for the population and water demand increase assumption scenarios are given in Table 7.17 while the results

for the population and water demand decrease assumption are provided in Table 7.18. In each ranking option, weights are multiplied by the normalized scores of each normalized value of technical and environmental sustainability criterion. The highest total score represents the favorable results with respect to the identified ranking option.

Table 7.17 Total scores for each ranking option for the population and water demand increase assumption scenarios under fire flow condition.

	Scenarios during fire flow	$SI_{network,pressure}$	$SI_{network,waterage}$	Energy Intensity	Total Freshwater Use	Total Score
RANK 1	New Pump	0.09	0	0.1	0	0.19
	Option A	**0.4**	**0.25**	**0.06**	**0.2**	**0.91**
	Option B	0.15	0.3	0.03	0.08	0.56
	Option C	0.03	0.25	0.00	0.2	0.48
	Option D	0	0.30	0	0.08	0.38
RANK 2	New Pump	0.07	0	0.1	0	0.17
	Option A	**0.3**	**0.33**	**0.06**	**0.2**	**0.89**
	Option B	0.11	0.4	0.03	0.08	0.62
	Option C	0.02	0.34	0.00	0.2	0.56
	Option D	0	0.40	0	0.08	0.48
RANK 3	New Pump	0.05	0	0.3	0	0.35
	Option A	**0.2**	**0.08**	**0.19**	**0.4**	**0.87**
	Option B	0.07	0.1	0.10	0.16	0.43
	Option C	0.01	0.08	0.01	0.4	0.51
	Option D	0	0.10	0	0.16	0.26
RANK 4	New Pump	0.05	0	0.4	0	0.45
	Option A	**0.2**	**0.08**	**0.25**	**0.3**	**0.83**
	Option B	0.07	0.1	0.13	0.12	0.43
	Option C	0.01	0.08	0.02	0.3	0.42
	Option D	0	0.10	0	0.12	0.22

Due to the normalization (i.e. score range) procedure, one criterion in each scenario option gets the value of "0". When normalized values are multiplied by weights, these criteria will still get the value of "0" in tables 7.17 and 7.18. In Table 7.17, option A of the reclaimed water for fire flow (i.e. Scenario VI) for the population and water demand increase assumption has the highest score for all of the ranking options since the "total score" for this scenario is the highest in each ranking alternative. For example, the total score of Scenario VI option A is "0.91" in rank 1 which is close to "1" while the Scenario V new pump has the lowest total score which is "0.19".

Based on Table 7.17, when there is an increasing population and water demand in the future, the Scenario V new pump is the worst alternative among the proposed scenarios to satisfy the technical sustainability criteria since this scenario gets the lowest scores in ranking alternatives 1 and 2. The Scenario VI option D has the lowest scores when the environmental sustainability is prioritized. Total scores are "0.26" and "0.22" in the ranking alternatives 3 and 4, respectively. This scenario option is energy intensive since the normalized value of this scenario is "0".

On the other hand, Table 7.18 shows that in the ranking options 1 and 2, the most favorable scenario is Option B (i.e. Scenario IX) when the technical sustainability criteria are prioritized for the population and water demand decrease assumption. Total scores of the Scenario IX option B are "0.75" and "0.76" in ranking alternatives 1 and 2, respectively. The Scenario IX option C has the highest score in the ranking alternatives 3 and 4 when the environmental criteria are given the highest weights.

Table 7.18 Total scores for each ranking option for the population and water demand decrease assumption scenarios under fire flow condition.

	Scenarios during fire flow	$SI_{network,pressure}$	$SI_{network,waterage}$	Energy Intensity	Total Freshwater Use	Total Score
RANK 1	New Pump	0	0.3	0.1	0	0.40
	Option A	0.4	0	0.01	0.2	0.61
	Option B	**0.32**	**0.26**	**0.10**	**0.08**	**0.75**
	Option C	0.22	0.01	0.10	0.2	0.53
	Option D	0.19	0.26	0	0.08	0.53
RANK 2	New Pump	0.00	0.4	0.1	0	0.50
	Option A	0.3	0	0.01	0.2	0.51
	Option B	**0.24**	**0.34**	**0.10**	**0.08**	**0.76**
	Option C	0.17	0.02	0.10	0.2	0.48
	Option D	0.14	0.35	0	0.08	0.57
RANK 3	New Pump	0	0.1	0.3	0	0.40
	Option A	0.2	0	0.02	0.4	0.62
	Option B	0.16	0.09	0.29	0.16	0.70
	Option C	**0.11**	**0.00**	**0.29**	**0.4**	**0.81**
	Option D	0.09	0.09	0	0.16	0.34
RANK 4	New Pump	0	0.1	0.4	0	0.50
	Option A	0.2	0	0.02	0.3	0.52
	Option B	0.16	0.09	0.39	0.12	0.75
	Option C	**0.11**	**0.00**	**0.39**	**0.3**	**0.81**
	Option D	0.09	0.09	0	0.12	0.30

CHAPTER 8

RESULTS & CONCLUSIONS

8.1   Summary and Results

Fresh water resources are limited and continue to decline around the world. Water stress due to climate change, population and water demand increase, urbanization, agricultural and industrial activities result in search for alternative solutions and water management activities. In addition, the existing fresh water supplies are facing the problem of water quality deterioration. Strategic decision-making plays an important role in overcoming the problems associated with the sustainable water resources planning.

8.1.1   Sustainability Index

Loucks (1997) introduced a SI calculation using reliability, resiliency, and vulnerability performance criteria to quantify and monitor sustainability of water supply over time. Once the desired satisfactory conditions are determined in terms of sustainability, this approach can assist in the comparison of sustainability for alternative current and future scenarios in the water resources field.

In this dissertation, the SI methodology using reliability, resiliency, and vulnerability performance criteria is used to assess the technical sustainability of an existing urban water distribution network. The nodal pressure and water age parameters are identified as hydraulic efficiency and water quality indicators, which are used to calculate reliability, resiliency, and vulnerability performance criteria. The EPANET software is used to calculate the nodal pressure and water age parameters (Rossman 2000). A hydraulic simulation is run for 144 hours, with only the time steps from 96 to 119 being utilized to observe pressure changes. The main reason for not using the first four days is that EPANET is using this period of time at the beginning of the

simulation to solve hydraulics and after reaching a certain balance, more accurate real world behavior is obtained. Once the hydraulic simulation is completed and the results for the nodal pressure and water age parameters are obtained for the time steps from 96 to 119 for each node, the performance criteria (i.e. reliability, resiliency and vulnerability) of each node are calculated.

These performance indicators for the nodal pressure and water age parameters for each node are then aggregated into the SI for nodal pressure and the SI for water age, respectively. In order to obtain an overall SI for each zone of the water network, the SI for pressure and the SI for water age are combined into an overall SI score for each zone. In this dissertation, the sustainability indices for nodal pressure and water age parameters are aggregated using equation 4.8, which is presented in Chapter 4, Section 4.2.6. The overall sustainability indices are used to identify problematic locations in the baseline scenario.

In order to calculate the technical sustainability scores for each scenario for the entire study area, equation 4.9 is used. The technical sustainability scores are calculated for the nodal pressure and water age separately. The results are used to conduct MCDA in order to evaluate scenarios that are proposed to solve the sustainability problems, which are identified based upon the results of the baseline scenario.

The SI methodology requires identifying thresholds for a parameter. For example, the lower and upper thresholds for the nodal pressure parameter for all scenarios are identified as 40 psi (P_{min} = 40 psi) and 80 psi (P_{max} = 80 psi) while the upper threshold for the water age parameter for all scenarios is 24-hours (WA_{max} = 24-hour). This means if the water age at a certain node is higher than 24-hours, the performance of the node in terms of water age is unsatisfactory.

Considering Scenario I: baseline, the SI calculation results show that the $SI_{pressure}$ scores for zones 1, 2, 3, 4, and 5 are 0.39, 0, 1, 0.89, and 0.03, respectively when the nodal pressure thresholds range from 40 psi to 80 psi. If these threshold values were set at 35 psi as a lower limit and 90 psi as an upper limit, then the $SI_{pressure}$ scores for zones 1, 2, 3, 4, and 5 would be 0.98, 0.10, 1, 1, and 0.26, respectively (see Table 8.1). The comparison of using different threshold values for the nodal pressure and water age parameters considering Scenario I: baseline is given in Table 8.1.

The overall sustainability indices (i.e. $SI_{overall}$) specifically for Zone 1 change significantly when the threshold values change for the nodal pressure and water age values. On the other hand, the $SI_{overall}$ for Zone 5 is still low considering the decision rule which is used in identifying the problematic locations in the WDS. According to the decision rule (see Table 4.2 in Chapter 5 Section 4.4.1), the $SI_{overall}$ lower than 0.25 is identified as "unacceptable" and assumed to be an unsustainable area, which requires alternative solutions to increase the sustainability.

Table 8.1 Sustainability index comparison of Scenario I: Baseline using different thresholds for the nodal pressure and water age parameters.

Scenario I: Baseline	P_{min} = 40 psi and P_{max} = 80 psi WA_{max} = 24-hour			P_{min} = 35 psi and P_{max} = 90 psi WA_{max} = 72-hour		
Zones	$SI_{pressure}$	$SI_{waterage}$	$SI_{overall}$	$SI_{pressure}$	$SI_{waterage}$	$SI_{overall}$
Zone 1	0.39	0.78	**0.59**	0.98	1	**0.99**
Zone 2	0	1	**0.50**	0.10	1	**0.55**
Zone 3	1	1	**1**	1	1	**1**
Zone 4	0.89	0.92	**0.91**	1	0.95	**0.98**
Zone 5	0.03	0.10	**0.07**	0.26	0.15	**0.21**

8.1.2 Scenario building

The goal here is to investigate the technical and environmental sustainability of the current urban WDS in terms of hydraulic efficiency and water quality as well as environmental sustainability criteria, and to propose alternative solutions for the identified problems in the current urban water network. The technical sustainability for the entire study area is identified as the SI in terms of the nodal pressure parameter while the environmental criteria are identified as the total fresh water use and energy intensity.

Alternative solutions are produced using the scenario analysis methodology. The scenarios for the current population and water demand are built considering traditional and more radical approaches. The scenario II: new pump is based on adding more network components such as booster pumps which is how the hydraulic efficiency and water quality problems are solved traditionally. The scenario III: the reclaimed water for fire flow scenarios are focusing on adding a separate water distribution network to meet the non-potable water demand as well as fire flow.

There are four sub-scenarios under scenario III: the reclaimed water for fire flow scenarios: using a reclaimed water network for non-potable water demand (option A), using reclaimed WDS for only outdoor irrigation and fire flow (option B), using a hybrid system for fire flow (i.e. fire flow demand should be satisfied using both potable and non-potable WDS) and a reclaimed water network for non-potable water demand (option C), using a hybrid system for fire flow and a reclaimed water network for only outdoor irrigation (option D).

Using a separate WDS to meet the non-potable water demand requires designing water networks. This design process for the non-potable water network is similar to designing a potable water distribution network. The design considerations for the non-potable water network are given in Table 4.4, in Chapter 4, Section 4.4.4. Since layouts for the non-potable water networks are considered to be branching types, a

linear programming approach is used to determine the pipe sizes and pumping head as well as the cost of the entire network for each Scenario III option.

8.1.3 Scenario evaluation

The main purpose of this dissertation is to analyze technical and environmental sustainability of a current WDS during fire flow conditions and to provide scenario-based solutions for the identified problems. Once the scenarios are proposed and technical and environmental sustainability criteria for each scenario and sub-scenario are calculated, the current water demand and population scenarios are compared with one another in order to evaluate the feasibility.

The results of the current population and water demand scenarios show that Scenario III Option B (i.e. using reclaimed water for outdoor water demand and fire flow) has the highest scores if decision makers prefer the technical sustainability of the water network over the environmental sustainability (see Table 6.13 in Chapter 6). On the other hand, Scenario III Option A is the most favorable alternative in ranking options 3 and 4 which prioritize the environmental sustainability criteria. Even though Scenario III options A and B have the highest scores in each ranking evaluation, normalized criteria show that using the non-potable water distribution network for fire flow and non-potable water demand is more energy consumptive than Scenario II the new pump scenario.

Another result is that the sustainability indices in terms of water age at Zone 5 in Scenario III options A and C are 0.09 and 0.37, respectively. These scores are the lowest of all the current water demand and population scenarios, which also affects the normalized scores of the entire network in terms of the technical sustainability. As can be seen in Table 6.13 in Chapter 6, the normalized scores for the $SI_{network,waterage}$ for Scenario III options A and C are 0 and 0.31, respectively. In both of these alternatives, base demands in potable WDS has been decreased extremely (i.e. approximately 75 %) which results in a high detention time at the nodes. In all of the ranking options provided here, using reclaimed water for the non-potable water demand and/or outdoor irrigation and fire flow has proven to be a feasible approach in terms of the technical and environmental sustainability. Specifically, large amounts of potable water can be saved by using dual water networks for fire flow.

In addition to the current water demand and population scenarios, the increasing and decreasing population and water demand prospects for the future urban WDS are investigated based upon assumptions. These assumptions are proposed considering the population and water demand change examples around the world. For example, the water demand in rural areas in Germany is expected to decrease by approximately 10 to 15 % in 2050, while the water demand and population in Arizona, USA is expected to increase by approximately 25 %.

Based upon these examples, in the decreasing population scenarios for future urban water network is assumed to be approximately 10 %. In the increasing population scenarios for future urban water network is assumed to be approximately 25 %. In future increase population scenarios, the water consumption per person is expected to decrease by the improved water demand management activities. Therefore, water demand per person for scenarios is 162 GPD. In both population and water demand increase and decrease assumptions, average velocities are calculated from time step 96 to 119 in order to determine the new pipe diameters in the water network. If the average velocity of the pipe is less than 0.15 m/s, the diameter of the corresponding pipe is decreased linearly to a smaller commercial size in order to analyze how the WDS would function if the current system had smaller pipe sizes.

While evaluating the future water demand and population variations, the same technical and environmental criteria are used together with the simple additive weighted aggregation. The "rank sum" weighting algorithm is used to calculate the weights for each ranking option which is provided in Chapter 4, Table 4.7. The ranks are given such that each criterion can be prioritized one at a time. This would allow decision makers and/or experts to choose the best option based upon their preferences.

Results of future water demand and population increase assumptions showed that Scenario VI Option A (i.e. using reclaimed water for non-potable indoor and outdoor water demand for fire flow) by far has the highest scores in all of the ranking options. This means that the most favorable option is Scenario VI Option A when the water demand and population increases in the future regardless of whether decision makers and/or experts prioritize environmental or technical sustainability. Specifically, the SI in terms of water age parameter at Zone 5 performing significantly better compared to the current population and water demand scenario (i.e. Scenario III Option A), namely the $SI_{waterage}$ in this scenario increased to 0.48 (see Table 7.7). Decreasing the diameters of water pipes with the velocities less than 0.15 m/s (approximately 0.47 ft/s) will assist in improving water ages in the water network when the population and water demand increases 25 %. In case of increasing population and water demand, Scenario V New Pump and Scenario VI Option D alternatives do not satisfy the requirements for the technical and environmental sustainability.

On the other hand, the most favorable scenario for population and water demand decreased assumptions vary based upon decision makers' and/or experts' preference of technical or environmental sustainability. For example, if the main priority is given to the technical sustainability, Scenario IX Option B (i.e. using reclaimed water for outdoor irrigation and fire flow) is the most favorable option since the MCDA results showed that this option has the highest total score. On the other hand, if the main priority is given to the environmental sustainability criteria, Scenario IX Option C (i.e. using reclaimed water for non-potable indoor and outdoor water demand and using potable and reclaimed water for fire flow) is the most promising alternative.

Although pipe diameters in all alternatives are decreased linearly to a smaller commercial size based on the average velocities of the pipes, the sustainability indices in terms of water age at Zone 5 in Scenario IX Options A and C still perform poorly which also performed poorly for the current population and water demand scenarios. Despite the decrease in size of pipe diameters, the low water demand at Zone 5 result in a high detention time.

8.1.4   Visualization approach

The scenario evaluation using the MCDA contains a large amount of data and the alternatives have to be represented to decision makers, experts, authorities and stakeholders. A DSS, which enables communication with these complex data sets, plays an important role in this process. Visualization tools and DSSs may improve the effectiveness of the entire decision process by incorporating knowledge into the data and eventually would assist in providing sustainable water services.

In this dissertation, the EPANET software is used to calculate the nodal pressure and water age parameters. The EPANET is an excellent tool for hydraulic simulations and water quality analysis. However, visualization capabilities are limited to creating thematic maps and/or using animation techniques to observe EPS results. In addition, depending on the size of water networks or proximity of nodes in the WDS, visibility of the nodes and pipes may deteriorate significantly.

Therefore, a visualization approach is proposed in this dissertation to represent the nodes and pipes for the case study. Several visualization techniques are combined to provide an effective representation of the WDS. The main parameters to visualize are the nodal pressures and water ages. The nodal pressure parameter gives information about the water availability at a specific location, while the water age represents the overall water quality in the WDS.

The nodal pressure and water age values for the study area are obtained as a function of operation time using the EPANET model. As an alternative to the animation technique, the time steps (i.e. from time step 96 to 119) are represented as small multiple maps. Small multiple maps require scaling down each map, which impacts the visibility of the nodes due to overlapping. Therefore, all the nodes along the edges are aggregated and represented as a single node. The circle view representation is used to visualize two values of the nodal pressure and water age variables. Even though the points are simplified after aggregating the edges, the distances between the points can still be irregular. In other words, the network may have dense points at one region that may result in overlapping circles and loss of visibility. Therefore, the water network is mapped onto a grid, which allows a user to see every node individually without overlaps.

In addition, an interactive tool is designed to assist decision makers in order to communicate with data. Since the original water network is modified visually, the

aim of interactive tool is to relate circle views with the original nodes as well as to accelerate the decision-making process by switching between the suggested scenarios, identifying problems with respect to the proposed sustainability assessment for the urban WDS. This interactive tool would also assist decision makers and/or experts in returning to the EPANET software for further simulations if necessary. The interactive tool, which is designed and modeled in this dissertation, is implemented by Alina Freund (Freund et al. 2014) in Java and utilizes the GUI library JavaFX due to its cross-platform and web-interface compatibility.

Shapefiles including the zones, nodes and pipes of the original water network which contains all information about each scenario are used as input data files while designing the interactive tool. Each data layer for the original data of each scenario (i.e. nodes) stores information about the water age and nodal pressure values for the simulation time step from 96 to 119, while the data layers for circle views for each scenario stores the data of "number of times the nodes along that edge are in satisfactory state" and "in unsatisfactory state" for the nodal pressures and water ages separately. All information is processed once in the beginning, after loading the data, the tool is able to provide all visualizations at any time point. This enables the user to utilize the UI without further possible delays because of intermediate I/O transactions.

Decision makers and/or experts are able to select a circle view for the desired scenario and immediately observe the sustainability indices for each zone for that particular scenario, as well as a time series graph for the selected parameter. Whereas creating graphs using the EPANET software requires certain knowledge about how the tools in the EPANET work. For example, in order to a graph for the nodal pressure parameter in the EPANET users first have to select a "graph" tool, then select a graph type (i.e. time series, profile plot, contour plot, frequency plot, system flow). After a user chooses a time series graph, a user also has to select a parameter (i.e. elevation, base demands, initial quality, demand, head, pressure, age) to create a graph. Finally, a user should add a node or a group of nodes to "Nodes to Graph" section. Although, the EPANET software provides a number of graph types for several parameters, creating a graph process can be confusing and time consuming for someone who has no experience with the software. In the case study of this dissertation, only the nodal pressure and water age parameters are subjects of interest since these parameters are used to calculate the technical sustainability of the WDS for each scenario. The proposed interactive tool provides graphs for the nodal pressures and water ages for the selected circle view, which contains a group of nodes without a time consuming process.

In addition, the reliability, resiliency and vulnerability concepts can be understood easily using the circle views. For example, the duration of yellow on the nodes indicates vulnerability while the frequency of the blue circle view indicates the reliability of the group of nodes. Aggregating the nodes along the edges simplifies

the network and gives better visual overview. However, all information of the aggregated group of nodes has to be shown.

Aggregating the nodes does not prevent overlaps where the nodes are densely located. The circle view representation is a way of displaying multiple variables on a single point. In this dissertation, "the number of times nodal pressure is satisfied" and "the number of times nodal pressure is not satisfied" are represented by the circle view. Depending on the size and density of the circle view, illustrating more than two values of a variable can be difficult to identify by decision makers. Visualizing the water network from a grid perspective is not a common approach in the water resources field. In this dissertation, overlapping of nodes in dense node areas is avoided using the grid representation while preserving the topology of the network. It is a more compact view, therefore coincides with the small multiple map view, which is better than the original network.

Overall, using small multiples instead of an animation gives broad information to the decision makers about the immediate changes in the network and the interactive tool facilitates this process. It is easier to follow each time step in the network, which is very crucial for the decision maker in the water resources field to be able to detect the low and too high pressures as well as high water ages. In addition, it is easy to observe the original data, create graphs and observe sustainability indices for the selected current water demand and population scenario. This tool assists decision makers and/or experts to identify the problems with the current network and take precautions to provide sustainable water services.

8.2   Conclusions

Providing environmental and technical sustainability in WDSs is becoming more challenging for authorities. The main purpose of this dissertation is to analyze the technical and environmental sustainability of an existing WDS and to provide a tool to support the decision-making process. Fire protection and firefighting criteria are an important attribute to design water networks since pipe sizes need to be designed to meet fire flow regulations. Consequently, a large amount of potable water storage as well as oversized pipes are required for the possibility of a fire event (Digiano et al. 2009).

Accordingly, the alternative scenarios for the current system and future population assumptions are focusing on using reclaimed water for fire flow and non-potable water demand. The scenarios are evaluated using MCDA. There is a wide range of multi-criteria analysis algorithms in literature and some examples are provided in the Chapter 2. Each method has its own specific area of use, properties, advantages and disadvantages (Ishizaka and Nemery 2013). The method that is chosen for this dissertation is based on the weighted summation technique which Janssen (2001)) states often provide a reliable solution. Specifically, the Simple Additive Weighting

method is used to aggregate the criteria while the "rank sum" method is used to calculate the weights. Using the MCDA in scenario evaluation is highly beneficial to reflect decision makers' preferences for current and future systems. In all scenario options for the current system and future population assumptions, using the reclaimed water for the non-potable water demand and fire flow is demonstrated to be feasible in terms of technical and environmental sustainability of the water network.

Considering the population and water demand increase assumption, total score for Scenario VI Option A (i.e. using reclaimed water for non-potable indoor and outdoor water demand and for fire flow) is significantly higher than the other scenarios. However, water pipe diameters are decreased in size while calculating the sustainability in this scenario option. If the existing pipe diameters were used, there could be hydraulic efficiency and water quality problems. The decision makers and/or experts should take into account the water network modifications while planning the sustainable water infrastructure for the future. In addition, the cost of any water network modification should be considered thoroughly.

On the other hand, the performance of the population and water demand decrease scenarios is slightly different from the population and water demand increase options. Based upon the decision makers and/or experts' priorities, the most favorable scenario is either Scenario IX Options B when the technical sustainability prioritized or Scenario IX Options C when the environmental sustainability is ranked in higher order. This result points out the importance of the decision makers and/or experts' preferences, future strategies should be clear and determined before planning urban water infrastructure.

Overall, the SI calculation using performance criteria (i.e. resiliency, reliability and vulnerability) for the technical sustainability of WDS has been shown to be a credible method of detecting problematic regions for decision makers and improving poor water services in fire flow conditions. The technical sustainability assessment methodology can improve the hydraulic and water quality performance of the network. However, thresholds for water age and pressure are site specific and need to be identified for each network based on expert knowledge or decision makers' preferences.

A standard way of displaying these time-varying performance measures for decision makers is the use of traditional animation techniques. In this dissertation, several visualization techniques are combined to eliminate problems associated with the animation technique and used to represent the nodal pressures and water ages in the WDS. In addition, an interactive tool is designed to facilitate the decision-making process. It is important to illustrate all the options and consequences of each option to decision makers and/or experts together with the method that is used for all evaluation. Using the interactive tool proposed in this dissertation enables decision makers to visually compare individual time steps as well as the results of each

current water system scenarios. In addition, the resiliency, reliability, and vulnerability performance indices can be understood easier than just using the EPANET software.

Interviews with the experts showed that the proposed visualization technique improves the visibility and enables an easy comparison. However, additional tools (i.e. displaying two or more scenarios at the same data frame) would improve the comparability of the tool. The color code explanation together with how the circle view functions need to be explained carefully to the decision makers. In addition, showing how the sustainable urban WDSs are supposed to perform in the circle view would be beneficial to decision makers for comparison purposes. In conclusion, the visualization approaches presented here as well as the interactive tool for the current population and water demand scenarios are beneficial for decision makers, stakeholders and/or experts who seek to provide sustainable urban water services.

8.3   Limitations

8.3.1   Data availability

In this dissertation, the proposed sustainability assessment and visualization approaches are applied to a medium size WDS with approximately 185 demand points. Current water demands are used to calculate hydraulic efficiency (i.e. nodal pressure) and water quality (i.e. water age). The historical information about water consumption in the study area is not available to perform a proper water demand forecast. Therefore, future population and water demand management scenarios are performed based on general population forecasts assumptions.

In addition, geographic and/or socio-economic information for the study area are not available. This information would be used to evaluate the future urban development area, which requires the extension of the WDS. Instead, the future requirements for water network extension are neglected while assessing the population increase and decrease scenarios. For example, Rao (2005) used geographic information such as slope of the study area, soil types, and land use as well as socio-economic factors such as population density, proximity to amenities (i.e. roads, railway stations, shopping centers, schools, banks etc.) to produce a future water demands. A demand map was used as a planning tool for future water management options in Dehradun City, India.

In this dissertation, due to the lack of data, the future urban water infrastructure development is not included in the scenario evaluation phase for the future population and water demand variations.

8.3.2 Future population, climate change, water use, and urban sprawl uncertainty

Even if the data were available to determine the future urban sprawl and required water infrastructure, the uncertainty on the development area prediction, population, climate change effect, availability of fresh water supply etc. still makes it difficult to have a definite plan for future WDS expansion or a plan based upon sustainability.

Scenario planning is a tool to improve the decision-making process and to deal with uncertainty (Varum and Melo 2007). Scenarios can be used to articulate the uncertainties. Variety in scenarios is important since it enables one to address all possibilities for the future, and to model more accessible probability distributions or deterministic models, and to conduct sensitivity analysis. The main point in scenario planning is to structure the problem based upon solid strategies or through expert communications (Stewart et al. 2013).

In this dissertation, a number of selected scenarios are proposed to address the uncertainty on water demand variation. On the other hand, more scenarios could be used to assess the uncertainty related to climate change and fresh water availability in the future. For example, climate change might result in increased residential water demand due to the extended duration of drought periods. On the other hand, climate change might also result in floods, which require different management policies for the future such as storm water management. Variations of climate change effects on water resources should be evaluated while building scenarios for future water demand as a result of population changes.

Finally, decision-making processes for planning urban water strategies involves further uncertainties such as evolving technologies for storm water harvesting, recycling waste water, time scale for analyzing urban water supply which would affect the decision makers preferences in a long-term (i.e. change of perception) (Moglia et al. 2012). In this dissertation, none of these uncertainties are considered or implemented into the sustainability assessment and scenario evaluation and comparison.

8.3.3 A more robust visualization tool to upload and analyse different water networks

In this dissertation, an interactive visualization tool is designed and created only for current system scenarios. This tool enables accessing the sustainability indices of the current system scenarios (i.e. Scenarios I: baseline, Scenario II: new pump, Scenario III: reclaimed water for fire flow) as well as visualizing the results of the nodal pressure and water age parameters for each time step using the proposed circle view visualization approach on the nodes.

Although future water demand and population scenarios are illustrated using the proposed visualization methodology, the scenario results were not included into the interactive DSS. The total number of scenarios increases when the future system

scenarios are included into the tool. Therefore, adding more scenarios would require using another function instead of using the combo box, which separates current system scenarios with the future ones. Adding a tab with two main data frames and selection tools which would enable choosing scenarios to be compared would be a beneficial property in order to facilitate the decision-making process for planning urban water infrastructure.

One problem of this visualization tool is that it can only be used for this case study area. The tool was not improved to upload any water network and visualize the network in a grid layout. Nor could it provide sustainability indices of the defined scenarios for any other study area. Including functions such as uploading any large scale WDS and visualizing the nodes and pipes in circle view approach on a grid layout automatically would require obtaining a more robust tool.

In addition, the interaction with decision makers is only limited to the available data that is stored in the database. For example, the tool created here visualizes the nodal pressure parameter in a circle view. The thresholds for the nodal pressure parameters are preset (i.e. satisfactory if the nodal pressure is in between 40 psi and 80 psi). Decision makers are not allowed to change these thresholds and visualize the results as circle views using this tool. In order to change the thresholds, the databases for each scenario for nodal pressure and/or water age parameters have to be changed for the desired satisfactory thresholds. On the other hand, adding "a query" function, which enables decision makers to set different thresholds for each parameter and immediately perceive the changes in circle views, could broaden the interaction. For example, the threshold for the water age parameter could be set to 72-hours instead of 24-hours and this would change the results of number of times that the nodes along the edges are in the satisfactory state and in the unsatisfactory state.

Considering different data sets (i.e. water networks), this function would not only improve the robustness but would be a prerequisite. The main reason is that the requirements, regulations, or decision-makers and/or experts opinion for different WDSs change in each country or state (Swamee and Sharma 2008). Therefore, if a user was able to upload any data, setting thresholds for nodal pressure and water age parameters specific to that particular data set would be an essential property of this interactive DSS.

Another issue is that the scenarios could only be observed one scenario at a time. There are two data frames in this interactive visualization tool; the main data frame is used to display the circle view approach and the other one is to provide original data for decision makers. In order to compare each scenario with another, the decision maker should be able to see the alternatives next to one another. This would assist in observing the alterations at each scenario for the nodal pressure and water age parameters as well as sustainability indices for each zone in each scenario.

As mentioned before, the interactive visualization tool only provides information for the current water demand scenarios. Basically, the data which are derived from the

EPANET software, and stored as shape files for each parameter of the corresponding scenario. This procedure (i.e. database management) is handled by exporting the hydraulic efficiency and the water quality simulation results from the EPANET software and arranging the tables to fit into shapefile format. This procedure could be incorporated into the decision support tool such that a decision maker would be able to automatically export the EPS results directly into the database. This would also support using other suggestions that were previously proposed (i.e. uploading different data sets). Decision makers could upload the data in the EPANET project format (i.e. .NET file) instead of converting the project files into shapefiles.

8.3.4 Alternative multi-criteria decision analysis methods instead of the ranking method

MCDA is widely and effectively used for scenario analysis in order to evaluate large-scale water resources management problems (Weng et al. 2010, Karolien et al. 2012). In this dissertation, the MCDA is used to aggregate the technical and environmental criteria based upon different priorities. in order to evaluate and compare the feasibility of each scenario the simple additive weighted aggregation method is utilized. For that purpose, weights are assigned to each criterion. The highest weight is given to the most favorable criterion. The "rank sum" method is used to calculate the weights.

Alternatively, creating weights and aggregating criteria to obtain an overall score for each scenario could be achieved using another weighting algorithm and aggregation method. For example, the pairwise comparison method developed by Saaty (1980) and used together with the Analytical Hierarchy Process (i.e. aggregation method) could be used to calculate the weights for the technical and environmental sustainability criteria. The pairwise comparison method is based upon a ratio matrix that is created using experts and/or decision makers' inputs of relatively comparing each criterion to one another. This ratio matrix is then normalized using the eigenvector with respect to the maximum eigenvalue at the matrix in order to determine the weights (Malczewski 1999).

In order to create a ratio matrix, decision makers or experts are given an intensity of importance scale from 1 to 9 representing "equal importance" and "extreme importance", respectively. Then, the weights are created using the information provided in ratio matrices. The consistency ratio is calculated in order to test the consistency of the comparison that was done by a decision maker and/or expert. If the consistency ratio is higher than 0.1, then decision makers and/or experts judgment is considered to be unreliable (Malczewski 1999).

The analytical hierarchy process can be used as a decision rule in order to aggregate the weights derived from the "pairwise comparison". This method is based on dividing a problem into different levels. While the highest level represents the main

goal in that particular decision problem secondary level represents alternatives. The problem could be further divided into levels depending on the complexity (Ishizaka and Nemery 2013). In this dissertation, the main goal is to evaluate the sustainability of an existing urban WDS. The first objective is to satisfy the technical sustainability, the second objective is to meet the environmental sustainability. The attributes for the first objective are the sustainability indices for the nodal pressure and water age while total freshwater use and energy intensity attributes belong to the environmental objective.

8.3.5 Different layout for the reclaimed WDS

The reclaimed WDS is designed using a linear programming approach since the dual water network was a branching system (i.e. dendritic/tree-type). The non-potable WDS is designed to satisfy non-potable water demands while the existing WDS (i.e. looped) serves potable water demands. Since the existing system corresponding to Zone 5 and part of Zone 4 was a looped type of water network, the dual water network could be designed as a looped system, as well. The size and other design parameters of this looped type of network would be completed using an optimization approach other than linear programming. Optimizing the design of a looped type of water networks have been extensively investigated in the literature. The available tools and historical progress of these optimization approaches are discussed by Lansey (2006). There are a number of tools that are available for optimizing the looped system such as linear programming gradient algorithm, a global optimization approach, genetic algorithms, non-linear programming etc. (Dan et al. 2007). The optimization approach depends on the availability and the purpose of the study.

In addition, in this dissertation, the current WDS was modified several times with respect to requirements of the proposed scenarios. For example, in the current population and water demand scenarios (i.e. Scenario II: new pump), additional network elements are included into the water distribution network. Although the pump schedules and/or the properties (i.e. pump curves) of the existing pumps, which are located at the close proximity of reservoirs, and the proposed booster pump were modified, they were not optimized based upon the proposed changes. In addition, as requirements for the reclaimed water for fire flow scenarios, base demands in the current WDS were reduced at Zone 5 and part of Zone 4. Using an optimization method to calibrate the pump schedules for the existing pumps would assist to reduce energy consumption and to have a feasible potable WDS. For example, Goldman and Mays (2005) proposed using simulated annealing in order to optimize the WDS operations including pump schedules together with the water quality.

8.4 Recommendation for future work

8.4.1 Including social and economic sustainability criteria

There are various ways defined in the literature to evaluate sustainability in general. One way of assessing sustainability is to use indicators to represent environmental, technical and socio-economic objectives. For example, Foxon et al. (2002) used indicators to assess the technical sustainability in the UK water industry. In this study, technical sustainability objectives were classified as performance, reliability, durability, and flexibility and adaptability. Reliability specifically is assessed using the following indicators: Water availability and distribution (i.e. fresh water availability), water use restrictions (i.e. percentage of the population that are subject to water use restrictions), pressure and interruption complaints (i.e. number of complaints that are received from customers), nodal pressures at the demand points, and risk of failure.

In this dissertation, technical sustainability is evaluated using the SI methodology. Reliability, resiliency and vulnerability are calculated as statistical measures for the WDS rather than indicator-based evaluation. In addition, sustainability of water infrastructure is evaluated based upon technical and environmental objectives. Social and economic objectives are not included in the analysis. In terms of social sustainability objectives, impacts of policy decision on human health, acceptability of scenarios to stakeholders, public participation, understanding and awareness can be included in the sustainability analysis (Foxon et al. 2002).

Economic objectives such as life cycle costs of each scenario (i.e. capital cost, end-use cost, remediation costs etc.), affordability for public, financial risks (Foxon et al. 2002) as well as operation and management costs can be included in the sustainability assessment of water infrastructure planning.

8.4.2 Multi objective optimization use

Evaluating water resources sustainability can be achieved using optimization approaches as well. In order to provide sustainable WDS, environmental and socio-economic objectives need to be considered together. Since there are number of objectives and conflicting issues, multi-objective optimization methods can be used to solve this decision-making problem. Multi-objective optimization approach is used when there are number of conflicting objectives that need to be satisfied. This circumstance requires tradeoffs among the objectives. Therefore, traditional optimality of a single-objective has to be replaced by the concept of "non-inferiority" in the multiple-objective analysis, which is based on a set of solution based upon maximizing conflicting objectives (Mays and Tung 1992).

Considering the case study in this dissertation, one approach could be using a multi-objective genetic algorithm using the following objectives:

Objective 1 – Minimize total capital cost and operation and management cost of urban water supply

Objective 2 – Maximize the environmental and technical sustainability of the entire urban water supply

Another way of evaluating the urban water distribution sustainability using an optimization technique would be based upon using a single objective of either maximizing the SI or minimizing the cost of the entire system. Following objectives are proposed for this purpose:

Example 1:

Objective: Minimize total capital cost and operation and management cost of urban water supply

Subject to:

Sustainability index of the entire system for the nodal pressure is greater than the identified threshold

Example 2:

Objective: Maximize the environmental and technical sustainability of the entire urban water supply

Subject to: Total capital cost and operation and management cost of urban water supply is less than the identified threshold

8.4.3 EPANET and sustainability index implementation

The sustainability indices for current and future population and water demand scenario assumptions are calculated using Microsoft excel using the results that are derived from the EPANET hydraulic and water quality simulations. For example, the EPS was applied to the baseline scenario for 144-hours. The EPANET software provides tools to export results of the EPS as tabular data. These reports can be observed using the Microsoft excel software. The EPS results from time step 96 to 119 for nodal pressure and water age results are stored in these files. Then, reliability, resiliency and vulnerability performance indicators are calculated for each node, which is then aggregated into sustainability indices of the zones for the nodal pressures and water ages. This process (i.e. the calculation of sustainability indices for each scenario) is simplified by using Microsoft Excel VBA (Visual Basic for Applications).

Another way to simplify this process would be to create a built-in tool in the EPANET software, which directly calculates sustainability indices for any urban WDS. This tool would make the process fast and easy for decision makers and/or experts who would not have to manipulate the results of the EPS. Evaluating reliability, resiliency and vulnerability of each node in urban WDSs directly using the

EPANET software would also assist not only sustainability problems but problems associated with the security and/or rehabilitation of water networks, design etc. This tool could enable the calculation of sustainability indices that decision makers and/or experts can define manually as well as to select zones/regions at the urban WDS where they wish to observe sustainability indices.

8.4.4   Wastewater and storm water as alternative water supplies

Here, the focus is on urban WDS sustainability. Using reclaimed water for fire flow and non-potable water demand scenarios are produced to achieve the sustainability through saving freshwater resources. This option has been thoroughly discussed in literature since the late 1990s. There are various ways to utilize reclaimed water as proposed in this dissertation; one way is to store reclaimed water and circulate through a separate WDS. On the other hand, the reclaimed water can also be used to recharge groundwater resources as in Windhoek, Namibia or in Tuscon, Arizona (Gleick 2000, Megdal 2007). This option should be investigated for future population and water demand scenarios in the study area.

In addition, not only wastewater reclamation but also rainwater and storm water harvesting could be considered for current and future populations and water demand scenarios. This option would also require further analysis for the storm water quantity and quality. Storm water sustainability, necessary changes of the storm water infrastructure should be investigated in case of using rainwater and storm water harvesting as alternative water supply.

In this dissertation, water age is considered as well as the water quality parameters to assess the sustainability of the urban WDS. However, chemical constituents and/or microbial pathogens in municipal wastewater should be investigated as a water quality parameter since current and future water demand and population scenarios focus on using reclaimed water to meet the fire flow and non-potable water demand. In addition, wastewater infrastructure alternatives should be investigated in the scenario analysis. Although the most commonly used in semi-urban, rural or remote areas, the decentralized and/or onsite wastewater treatment systems should be included into the sustainability assessment of urban water infrastructure (Asano et al. 2007).

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Publications	*Journal*
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APPENDICES

APPENDIX 1

THE EPANET INPUT FILE

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[TITLE]


[JUNCTIONS]
;ID             Elev            Demand          Pattern
 3              569.69          0               2                       ;
 4              603.86          0               2                       ;
 FH-1           603.88          0               2
        ;FH-1
 6              591.94          0               2                       ;
 7              320.59          0               2                       ;
 9              546.65          0               2                       ;
 10             514.08          0               2                       ;
 11             512.78          0               2                       ;
 12             512.31          2               2                       ;
 13             513.54          1               2                       ;
 14             562             1               2                       ;
 15             542.22          0.2             2                       ;
 16             550             1               2                       ;
 17             558.07          0.5             2                       ;
 18             595.54          0               2                       ;
 19             478.05          0.5             2                       ;
 20             538.11          0               2                       ;
 21             471.6           2               2                       ;
 22             494.93          0               2                       ;
 23             496.51          .5              2                       ;
 FH-2           494.86          0               2                       ;
 25             491.54          .5              2                       ;
 26             491.03          .2              2                       ;
 FH-3           490.4           2               2                       ;
 28             486.12          .2              2                       ;
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29	490	.3	2	;
30	490.75	.2	2	;
31	491.1	0	2	;
32	491	.2	2	;
33	491	0	2	;
34	494.95	.2	2	;
35	495.24	.2	2	;
FH-4	496.03	.2	2	;
37	495.49	.2	2	;
38	492.92	0	2	;
39	495.06	1	2	;
FH-7	495.58	1.54	2	;
FH-5	498.04	0	2	;
42	497.09	0	2	;
FH-8	496.34	0	2	;
FH-9	494.89	1.54	2	;
FH-10	497.3	1	2	;
46	497.51	1	2	;
47	497.51	0	2	;
48	573.63	0	2	;
49	454.34	2	2	;
50	459.77	2	2	;
51	456.86	3	2	;
53	453.62	0	2	;
54	453.71	2	2	;
55	455.89	3	2	;
56	456.11	0	2	;
57	456.28	3	2	;
58	456.1	2	2	;
FH-21	458.64	0	2	;
60	456.95	3	2	;
61	456.78	3	2	;
62	460.55	0	2	;
63	457.86	2	2	;
64	462.26	6	2	;
FH-23	462.14	14	2	;
66	459.38	2	2	;
67	458.4	0.5	2	;
68	457.86	4	2	;
FH-24	455.77	2	2	;
70	468.36	8	2	;
71	468.83	4	2	;
FH-25	467.08	0	2	;
FH-26	459.35	5	2	;
FH-27	456.55	5	2	;
75	456.43	0	2	;
FH-29	453.68	4	2	;
77	454.02	4	2	;
78	457.64	5	2	;
80	465.92	1	2	;
FH-31	461.18	0	2	;
82	461.5	4	2	;
83	460.98	4	2	;
84	460.06	0	2	;
85	465.6	4	2	;
86	455.03	5	2	;
87	454.02	4	2	;FH
88	471.93	9	2	;
89	496.61	5	2	;
90	492.99	3	2	;GV
92	467.34	2	2	;
93	455.07	1.54	2	;
94	450.54	1	2	;
95	442.24	0	2	;
96	499.65	1.54	2	;
97	499.92	1.54	2	;

```
FH-16            499.74           1.54           2                    ;
99               497.49           1.54           2                    ;
100              498.92           .4             2                    ;
101              498.87           .4             2                    ;
102              498.63           .4             2                    ;
FH-12            498              .5             2                    ;
FH-11            497.63           1              2                    ;
105              495.66           .07            2                    ;
106              502.41           .09            2
     ;Clinic Tie-In
107              486.11           0              2                    ;
108              497.70           .4             2                    ;
109              495.52           .4             2                    ;
110              495              1              2                    ;
111              496.39           .5             2                    ;
112              495.3            2              2                    ;
113              491.08           3              2                    ;
114              590.59           0              2                    ;
116              333              0              2                    ;
117              603              0              2                    ;
118              496              0              2                    ;
FH-6             496              1.54           2                    ;
121              467.34           1              2                    ;
124              471.85           0.5            2                    ;
FH-33            480.1            4              2
     ;Campground & Irrigation
127              478              5              2                    ;
128              481              8              2                    ;
129              470              4              2                    ;
FH-39            493              .44            2                    ;
131              475              3.34           2                    ;
132              481              3.34           2                    ;
133              486              3.34           2                    ;
134              487              3.34           2                    ;
135              490              3.35           2                    ;
136              507              2              2                    ;
FH-45            518              0              2                    ;
138              525              5              2                    ;
139              568              1              2                    ;
140              567              6              2                    ;
141              527              7              2                    ;
142              559              2              2                    ;
143              525              5              2                    ;
144              525              1              2                    ;
FH-44            528              1              2                    ;
FH-43            508              1.19           2                    ;
FH-42            500              1.19           2                    ;
148              478              4              2                    ;
149              487              .44            2                    ;
150              472              5              2                    ;
FH-38            474              6              2                    ;
152              480              9              2                    ;
153              486              1.9            2                    ;
154              485              3              2                    ;
155              482              10             2                    ;
FH-34            480              10             2                    ;
FH-13            500              1.54           2                    ;
FH-14            501.6            1.54           2                    ;
FH-15            501.2            1.54           2                    ;
5                458.4            3              2                    ;
FH-17            458              5              2                    ;
FH-18            454              2              2                    ;
27               460              6              2                    ;
FH-19            456              3              2                    ;
FH-20            454              0              2                    ;
36               456              4              2                    ;
```

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```
FH-22            452            1            2            ;
FH-28            463.5          0            2            ;
FH-30            456            2            2            ;
FH-32            460.5          2            2            ;
FH-35            473.2          8            2
     ;Old Mobile Home Park
FH-36            474.5          10           2
     ;OMP Irrigation
FH-37            461            4.43         2            ;
FH-40            485            1.19         2            ;
FH-41            491            1.19         2            ;
2                518            3            2            ;
24               463            3            2            ;
41               475            .48          2
     ;Thunderhead E
40               569            0            2            ;
43               484            30           2            ;
8                541            0.2          2            ;
44               516            0            2            ;
45               494            1            2            ;
65               593            0            2            ;
69               593            0            2            ;
72               593            0            2            ;
73               592            0            2            ;
76               592            0            2            ;
79               622            0            2            ;
81               622            0            2            ;
91               593            0            2            ;
98               593            0            2            ;
```

[RESERVOIRS]
```
;ID              Head           Pattern
 52              449.59                      ;
 115             449                         ;
```

[TANKS]
```
;ID              Elevation      InitLevel      MinLevel
     MaxLevel         Diameter       MinVol         VolCurve
 T-1             596.5          20             0            24
     32               0                         ;
 T-3             536            40             10           48
     48               0                         ;
 T-2             596.5          20             0            24
     35               0                         ;
```

[PIPES]
```
;ID              Node1          Node2          Length
     Diameter         Roughness      MinorLoss       Status
 9               9              10             2066.37      5
     130              0              Open        ;
 10              10             11             14.77        7
     130              0              Open        ;
 11              11             12             5.94         8
     130              0              Open        ;
 12              12             13             21.34        8
     130              0              Open        ;
 13              13             14             95.66        8
     130              0              Open        ;
 14              14             15             298.00       2
     120              0              Open        ;
 15              14             16             295.81       8
     130              0              Open        ;
 16              16             17             197.62       2
     120              0              Open        ;
 17              16             18             729.52       8
     130              0              Open        ;
```

18	130	18	0	19	Open	1074.97	8	;
19	130	19	0	20	Open	1311.51	8	;
20	130	20	0	21	Open	53.15	8	;
21	130	21	0	22	Open	642.56	8	;
22	130	22	0	23	Open	114.49	8	;
23	120	23	0	FH-2	Open	60.52	6	;
24	120	FH-2	0	25	Open	471.16	6	;
25	120	25	0	26	Open	56.77	6	;
26	120	26	0	FH-3	Open	37.76	6	;
27	120	FH-3	0	28	Open	59.58	6	;
28	120	28	0	29	Open	173.60	6	;
29	120	29	0	30	Open	34.11	6	;
30	120	30	0	31	Open	30.46	5	;
31	120	31	0	32	Open	302.01	6	;
32	120	32	0	33	Open	54.14	6	;
33	120	33	0	34	Open	55.06	6	;
34	120	34	0	35	Open	107.73	6	;
35	120	35	0	37	Open	63.07	6	;
36	120	37	0	FH-4	Open	92.88	9	;
37	120	37	0	38	Open	248.51	6	;
38	120	38	0	39	Open	147.66	6	;
39	120	39	0	FH-7	Open	221.05	6	;
40	120	FH-7	0	FH-5	Open	619.37	6	;
41	120	FH-5	0	42	Open	137.47	6	;
42	120	42	0	FH-8	Open	189.31	6	;
43	120	FH-8	0	FH-9	Open	354.79	6	;
44	120	FH-9	0	FH-10	Open	827.90	6	;
45	120	FH-10	0	47	Open	184.40	8	;
46	120	47	0	46	Open	56.39	6	;
47	120	20	0	48	Open	1319.43	8	;
49	120	49	0	27	Open	191.45	8	;
50	120	50	0	51	Open	234.04	6	;
51	120	51	0	53	Open	183.85	6	;

52	120	53	0	54	Open	23.87	4	;
53	130	54	0	FH-20	Open	135.17	6	;
54	120	55	0	56	Open	35.17	6	;
55	120	56	0	57	Open	78.69	6	;
56	120	57	0	58	Open	110.50	6	;
57	120	58	0	FH-21	Open	11.65	6	;
58	120	FH-21	0	60	Open	15.20	6	;
59	120	60	0	51	Open	296.14	6	;
60	120	50	0	61	Open	513.00	8	;
61	120	61	0	36	Open	251.27	10	;
62	120	62	0	63	Open	58.43	6	;
63	120	62	0	64	Open	895.47	6	;
64	120	64	0	FH-23	Open	177.66	12	;
65	120	FH-23	0	66	Open	212.58	8	;
66	120	64	0	70	Open	557.33	8	;
67	120	70	0	71	Open	306.15	8	;
68	120	71	0	FH-25	Open	192.86	8	;
69	120	FH-25	0	FH-26	Open	461.75	8	;
70	120	FH-26	0	FH-27	Open	351.89	8	;
71	120	FH-27	0	75	Open	91.24	8	;
72	120	75	0	FH-29	Open	149.94	8	;
73	120	FH-29	0	77	Open	279.38	6	;
74	120	77	0	78	Open	122.43	6	;
76	120	71	0	80	Open	1276.32	8	;
77	120	80	0	FH-31	Open	235.11	6	;
78	120	FH-31	0	82	Open	41.91	6	;
79	120	82	0	83	Open	34.57	6	;
80	120	83	0	84	Open	86.46	6	;
81	120	80	0	85	Open	494.63	8	;
84	120	86	0	87	Open	226.49	6	;
85	120	89	0	90	Open	374.85	6	;
88	120	92	0	93	Open	290.64	4	;
89	120	93	0	94	Open	54.19	4	;

90	94	95	20.21	4
120	0	Open	;	
91	96	97	58.75	12
120	0	Open	;	
92	97	FH-16	752.56	8
120	0	Open	;	
93	FH-16	99	661.79	8
120	0	Open	;	
94	100	101	51.92	6
120	0	Open	;	
95	101	102	33.31	6
120	0	Open	;	
96	102	FH-12	576.25	6
120	0	Open	;	
98	FH-12	FH-11	479.95	6
120	0	Open	;	
99	FH-11	105	117.33	6
120	0	Open	;	
100	105	106	130.36	8
120	0	Open	;	
101	105	107	1287.11	6
120	0	Open	;	
102	107	20	1836.51	6
120	0	Open	;	
103	FH-11	108	473.63	6
120	0	Open	;	
104	108	109	197.93	6
120	0	Open	;	
105	109	110	97.72	6
120	0	Open	;	
106	110	111	61.83	4
120	0	Open	;	
107	111	112	57.46	6
120	0	Open	;	
108	112	113	131.03	8
120	0	Open	;	
109	113	28	90.40	8
120	0	Open	;	
110	114	7	51.23	4
120	0	Open	;	
112	116	117	270	4
120	0	Open	;	
113	117	4	53.26	8
120	0	Open	;	
115	100	89	334.60	6
120	0	Open	;	
116	89	118	296.00	6
120	0	Open	;	
117	118	FH-6	282.20	6
120	0	Open	;	
118	FH-6	FH-7	333.75	6
120	0	Open	;	
120	66	67	49.68	6
120	0	Open	;	
121	67	68	55.37	6
120	0	Open	;	
122	68	FH-24	111.78	6
120	0	Open	;	
123	90	121	57.63	6
120	0	Open	;	
136	149	148	502.12	8
120	0	Open	;	
137	148	131	363.00	6
140	0	Open	;	
139	FH-42	FH-43	182.33	6
120	0	Open	;	

ID	Node1	Node2	Length	Diameter	Roughness	Minor Loss	Status	
140	FH-43	FH-44	537.83	6	120	0	Open	;
141	131	132	136.23	6	140	0	Open	;
142	132	133	879.55	10	140	0	Open	;
143	133	134	197.20	6	140	0	Open	;
144	134	135	332.58	8	140	0	Open	;
145	134	135	332.58	8	120	0	Open	;
146	135	136	179.79	8	140	0	Open	;
147	FH-45	136	96.89	8	120	0	Open	;
86	121	92	31.02	6	120	0	Open	;
131	127	128	370.39	6	120	0	Open	;
149	FH-45	T-3	168.58	10	140	0	CV	;
157	FH-44	FH-45	323.60	8	120	0	Open	;
158	FH-45	138	112.75	6	120	0	Open	;
159	138	139	450.07	6	120	0	Open	;
160	139	140	397.04	6	120	0	Open	;
161	140	141	199.15	6	120	0	Open	;
162	141	142	98.97	6	120	0	Open	;
163	142	143	257.06	6	120	0	Open	;
164	143	144	199.47	6	120	0	Open	;
165	129	FH-39	934.22	8	120	0	Open	;
166	128	129	401.44	8	120	0	Open	;
167	149	150	253.45	8	120	0	Open	;
168	150	FH-38	377.43	6	120	0	Open	;
169	FH-38	154	499.25	6	120	0	Open	;
170	FH-38	152	560.26	6	120	0	Open	;
171	152	153	233.84	8	120	0	Open	;
172	155	FH-34	89.29	6	120	0	Open	;
173	FH-33	155	437.15	6	120	0	Open	;
174	124	FH-33	567.21	6	120	0	Open	;
175	88	124	150.48	6	120	0	Open	;
6	FH-1	4	519.29	6	120	0	Open	;
7	6	FH-1	737.62	8	130	0	Open	;
8	114	6	170.75	8	120	0	Open	;

2	120	4	0	3	Open	13966.91	8	;
87	130	100	0	FH-13	Open	224.59	6	;
97	130	FH-13	0	FH-14	Open	434.10	6	;
127	130	FH-14	0	FH-15	Open	311.49	6	;
128	130	FH-15	0	96	Open	414.16	8	;
130	130	5	0	49	Open	349.51	8	;
150	130	48	0	5	Open	129.02	8	;
151	130	5	0	FH-17	Open	153.71	6	;
152	130	FH-17	0	FH-18	Open	357.96	6	;
177	130	27	0	50	Open	228.59	8	;
178	130	27	0	FH-19	Open	278.10	6	;
179	130	FH-20	0	55	Open	177.12	6	;
180	130	36	0	FH-22	Open	260.41	6	;
181	130	36	0	62	Open	270.64	8	;
182	130	FH-27	0	FH-28	Open	324.49	8	;
183	130	78	0	FH-30	Open	114.30	6	;
5	130	85	0	FH-32	Open	502.16	8	;
48	130	FH-32	0	86	Open	154.59	6	;
75	130	FH-34	0	FH-35	Open	479.80	6	;
82	130	FH-35	0	127	Open	580.71	6	;
119	130	155	0	FH-36	Open	883.65	6	;
124	130	FH-36	0	154	Open	577.75	6	;
125	130	128	0	FH-37	Open	271.19	6	;
126	130	128	0	FH-37	Open	271.19	4	;
129	130	148	0	FH-40	Open	257.71	8	;
132	130	T-3	0	2	CV	156.78	8	;
133	130	2	0	FH-45	Open	18.25	8	;
134	130	FH-40	0	FH-41	Open	127.52	10	;
135	130	FH-41	0	FH-42	Open	158.23	8	;
138	130	85	0	24	Open	703.86	10	;
148	130	24	0	88	Open	673.49	8	;
154	130	131	0	41	Open	583.34	6	;
156	130	40	0	9	Open	1431.66	6	;

176	155	43	598.18	6
130	0	Open	;	
3	40	8	1453.63	6
130	0	Open	;	
4	8	44	2213.22	8
130	0	Open	;	
184	44	45	644.35	6
130	0	Open	;	
185	45	71	2388.56	8
130	0	Open	;	
195	81	T-1	7.95	8
130	0	Open	;	
196	3	91	1118.18	8
130	0	Open	;	
199	98	40	1106.54	8
130	0	Open	;	
1	T-2	79	8.21	8
130	0	Open	;	
187	T-2	73	43.15	12
130	0	Open	;	
188	73	76	58.53	12
130	0	Open	;	
189	76	98	104.68	8
130	0	Open	;	
190	91	65	123.95	8
130	0	Open	;	
191	65	72	89.04	10
130	0	Open	;	
192	65	69	39.15	6
130	0	Open	;	
193	T-1	76	23.00	8
130	0	Open	;	

[PUMPS]
;ID   Node1   Node2   Parameters
 111   52   7   HEAD 4   ;
 114   115   116   HEAD 1   ;

[VALVES]
;ID   Node1   Node2   Diameter
     Type Setting   MinorLoss
 83   72   79   12   PSV
     0   0   ;
 153   69   81   12   PSV
     0   0   ;

[TAGS]
 NODE   FH-2   FH-2
 NODE   FH-3   FH-3
 NODE   FH-4   FH-4
 NODE   FH-7   FH-7
 NODE   FH-5   FH-5
 NODE   FH-8   FH-8
 NODE   FH-9   FH-9
 NODE   FH-10   FH-10
 NODE   FH-21   FH-21
 NODE   FH-23   FH-23
 NODE   FH-24   FH-24
 NODE   FH-25   FH-25
 NODE   FH-26   FH-26
 NODE   FH-27   FH-27
 NODE   FH-29   FH-29
 NODE   FH-31   FH-31
 NODE   FH-16   FH-16
 NODE   FH-12   FH-12
 NODE   FH-11   FH-11

```
NODE       105              WaterDept
NODE       106              Clinic
NODE       FH-6             FH-6
NODE       FH-33            FH-33
NODE       FH-39            FH-39
NODE       FH-45            FH-45
NODE       FH-44            FH-44
NODE       FH-43            FH-43
NODE       FH-42            FH-42
NODE       FH-38            FH-38
NODE       FH-34            FH-34
NODE       FH-13            FH-13
NODE       FH-14            FH-14
NODE       FH-15            FH-15
NODE       FH-17            FH-17
NODE       FH-18            FH-18
NODE       FH-19            FH-19
NODE       FH-20            FH-20
NODE       FH-28            FH-28
NODE       FH-30            FH-30
NODE       FH-32            FH-32
NODE       FH-35            FH-35
NODE       FH-36            FH-36
NODE       FH-37            FH-37
NODE       FH-40            FH-40
NODE       FH-41            FH-41
LINK       9                Proposed
LINK       10               Proposed
LINK       11               Proposed
LINK       12               Proposed
LINK       13               Proposed
LINK       15               Proposed
LINK       17               Proposed
LINK       18               PVC14YRS
LINK       19               PVC14YRS
LINK       20               PVC14YRS
LINK       21               PVC14YRS
LINK       22               PVC24YRS
LINK       24               PVC24YRS
LINK       25               PVC24YRS
LINK       26               PVC24YRS
LINK       27               PVC24YRS
LINK       28               PVC24YRS
LINK       29               PVC24YRS
LINK       30               PVC24YRS
LINK       31               PVC24YRS
LINK       32               PVC24YRS
LINK       33               PVC24YRS
LINK       34               PVC24YRS
LINK       35               PVC24YRS
LINK       36               PVC24YRS
LINK       37               PVC24YRS
LINK       38               PVC24YRS
LINK       39               PVC24YRS
LINK       40               PVC24YRS
LINK       42               PVC24YRS
LINK       43               PVC24YRS
LINK       96               PVC24YRS
LINK       98               PVC24S
LINK       103              PVC24YRS
LINK       104              PVC24YRS
LINK       105              PVC24YRS
LINK       106              PVC24YRS
LINK       107              PVC24YRS
LINK       108              PVC24YRS
LINK       109              PVC24YRS
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 LINK        115             PVC24YRS
 LINK        116             PVC24YRS
 LINK        117             PVC24YRS
 LINK        6               PVC14YRS
 LINK        7               PVC14YRS
 LINK        8               PVC14YRS
 LINK        2               PVC14YRS


[DEMANDS]
;Junction         Demand           Pattern          Category

[STATUS]
;ID               Status/Setting

[PATTERNS]
;ID               Multipliers
;
 2                0.4              0.4              0.3              0.3
      0.5              0.5
 2                1.5              1.5              1.5              1.1
      1.1              1
 2                1                1.1              1.1              1.2
      1.2              1.5
 2                1.5              1.5              1.3              1.3
      0.6              0.6

[CURVES]
;ID               X-Value          Y-Value
;PUMP: Floway 6 stage vertical turbine
 1                0                360
 1                100              350
 1                250              330
 1                300              320
 1                400              300
 1                500              265
 1                600              220
 1                700              170
;EFFICIENCY: Floway, 6 stage, vertical turbine efficiency curve
 2                200              56
 2                300              70
 2                400              78
 2                525              80
 2                550              81
 2                600              81
 2                650              79
 2                700              75
 2                800              62
;PUMP: Floway 6 stage, vertical turbine pump curve 6.25" min
 3                0                260
 3                300              250
 3                500              225
 3                600              195
 3                700              160
 3                750              140
 3                800              110
 3                850              90
;PUMP: Floway 6 stage, vertical turbine Midway between 7.3 in and 6.2
in
 4                0                325
 4                150              310
 4                350              290
 4                450              260
 4                550              210
 4                600              190
 4                650              160
 4                700              120
```

190

```
[CONTROLS]

[RULES]
RULE 1
IF TANK T-1 LEVEL ABOVE 24
THEN PUMP 111 STATUS IS CLOSED

RULE 3
IF TANK T-1 LEVEL BELOW 10
THEN PUMP 114 STATUS IS OPEN

RULE 4
IF TANK T-1 LEVEL ABOVE 13
THEN PUMP 114 STATUS IS CLOSED

RULE 2
IF TANK T-1 LEVEL BELOW 10
THEN PUMP 111 STATUS IS OPEN

RULE 5
IF TANK T-3 LEVEL BELOW 20
THEN PUMP 114 STATUS IS OPEN

RULE 6
IF TANK T-3 LEVEL ABOVE 30
THEN PUMP 114 STATUS IS CLOSED




[ENERGY]
 Global Efficiency      75
 Global Price           0
 Demand Charge          0
 Pump      111                 Efficiency 2
 Pump      111                 Price      .11
 Pump      114                 Efficiency 2
 Pump      114                 Price      .11

[EMITTERS]
;Junction        Coefficient

[QUALITY]
;Node            InitQual

[SOURCES]
;Node            Type            Quality         Pattern

[REACTIONS]
;Type      Pipe/Tank      Coefficient


[REACTIONS]
 Order Bulk                1
 Order Tank                1
 Order Wall                1
 Global Bulk               0
 Global Wall               0
 Limiting Potential        0
 Roughness Correlation     0

[MIXING]
;Tank            Model
```

```
[TIMES]
 Duration            144
 Hydraulic Timestep  1
 Quality Timestep    0:02
 Pattern Timestep    1
 Pattern Start       0:00
 Report Timestep     1:00
 Report Start        0:00
 Start ClockTime     12 am
 Statistic           None

[REPORT]
 Status              No
 Summary             No
 Page                0

[OPTIONS]
 Units               GPM
 Headloss            H-W
 Specific Gravity    1
 Viscosity           1
 Trials              40
 Accuracy            0.001
 CHECKFREQ           2
 MAXCHECK            10
 DAMPLIMIT           0
 Unbalanced          Continue 10
 Pattern             1
 Demand Multiplier   1
 Emitter Exponent    0.5
 Quality             Age mg/L
 Diffusivity         1
 Tolerance           0.01



[BACKDROP]
 DIMENSIONS     37448.20        14058.89        49870.73
      42884.12
 UNITS          None
 FILE
 OFFSET         0.00            0.00

[END]
```

APPENDIX 2

INTERACTIVE DECISION SUPPORT TOOL

LINK

```
/*
 * To change this license header, choose License Headers in Project
Properties.
 * To change this template file, choose Tools | Templates
 * and open the template in the editor.
 */

package masterproject;

import java.util.ArrayList;

/**
 *
 * @author Alina
 */
public class Link {

    ArrayList<Double> x = new ArrayList();
    ArrayList<Double> y = new ArrayList();
    double length = 0;
    int line_width = 25;
    int id = -1;
    int simpleID = -1;

    public Link() {
        // nothing to do here
    }

    public ArrayList<Double> getX() {
        return x;
    }

    public void setX(ArrayList<Double> x) {
        this.x = x;
```

```java
    }

    public ArrayList<Double> getY() {
        return y;
    }

    public void setY(ArrayList<Double> y) {
        this.y = y;
    }

    public double getLength() {
        return length;
    }

    public void setLength(double length) {
        this.length = length;
    }

    public int getLine_width() {
        return line_width;
    }

    public void setLine_width(int line_width) {
        this.line_width = line_width;
    }

    public int getId() {
        return id;
    }

    public void setId(int id) {
        this.id = id;
    }

    public int getSimpleID() {
        return simpleID;
    }

    public void setSimpleID(int simpleID) {
        this.simpleID = simpleID;
    }

}
```

NODE

```java
/*
 * To change this license header, choose License Headers in Project
Properties.
 * To change this template file, choose Tools | Templates
 * and open the template in the editor.
 */

package masterproject;

import java.util.ArrayList;

/**
 *
 * @author Alina
 */
public class Node {

    double x = 0;
    double y = 0;
```

```java
String id = "-1";
int simpleID = -1;
double total = -1;
String zoneId = "";
double[] satPressure = new double[24]; //from 96 up to 119
double[] pressGrad = new double[23];
double[] satAge = new double[24];
double[] ageGrad = new double[23];
ArrayList<double[]> pre = new ArrayList();
ArrayList<double[]> qua = new ArrayList();
ArrayList<String> preIds = new ArrayList();
ArrayList<String> quaIds = new ArrayList();

public Node() {
    //nothing to do here
}

public double getX() {
    return x;
}

public void setX(double x) {
    this.x = x;
}

public double getY() {
    return y;
}

public void setY(double y) {
    this.y = y;
}

public String getId() {
    return id;
}

public void setId(String id) {
    this.id = id;
}

public int getSimpleID() {
    return simpleID;
}

public void setSimpleID(int simpleID) {
    this.simpleID = simpleID;
}

public double getTotal() {
    return total;
}

public void setTotal(double total) {
    this.total = total;
}

public String getZoneId() {
    return zoneId;
}

public void setZoneId(String zoneId) {
    this.zoneId = zoneId;
}

public double[] getSatPressure() {
```

```java
        return satPressure;
    }

    public void setSatPressure(double[] satPressure) {
        this.satPressure = satPressure;
    }

    public double[] getPressGrad() {
        return pressGrad;
    }

    public void setPressGrad(double[] pressGrad) {
        this.pressGrad = pressGrad;
    }

    public double[] getSatAge() {
        return satAge;
    }

    public void setSatAge(double[] satAge) {
        this.satAge = satAge;
    }

    public double[] getAgeGrad() {
        return ageGrad;
    }

    public void setAgeGrad(double[] ageGrad) {
        this.ageGrad = ageGrad;
    }

    public void calcPressGrad() {
        for (int i = 0; i < 23; i++) {
            this.pressGrad[i] = Math.abs(this.satPressure[i] -
this.satPressure[i+1]);
        }
    }

    public void calcAgeGrad() {
        for (int i = 0; i < 23; i++) {
            this.ageGrad[i] = Math.abs(this.satAge[i] -
this.satAge[i+1]);
        }
    }

    public ArrayList<double[]> getPre() {
        return pre;
    }

    public void setPre(ArrayList<double[]> pre) {
        this.pre = pre;
    }

    public ArrayList<double[]> getQua() {
        return qua;
    }

    public void setQua(ArrayList<double[]> qua) {
        this.qua = qua;
    }

    public ArrayList<String> getPreIds() {
        return preIds;
    }

    public void setPreIds(ArrayList<String> preIds) {
```

```
        this.preIds = preIds;
    }

    public ArrayList<String> getQuaIds() {
        return quaIds;
    }

    public void setQuaIds(ArrayList<String> quaIds) {
        this.quaIds = quaIds;
    }

}
```

ZONE

```
/*
 * To change this license header, choose License Headers in Project
Properties.
 * To change this template file, choose Tools | Templates
 * and open the template in the editor.
 */

package masterproject;

import java.util.ArrayList;

/**
 *
 * @author Alina
 */
public class Zone {

    ArrayList<Double> x = new ArrayList();
    ArrayList<Double> y = new ArrayList();
    int id = -1;
    String name = "";

    public Zone() {
        //nothing to do here
    }

    public ArrayList<Double> getX() {
        return x;
    }

    public void setX(ArrayList<Double> x) {
        this.x = x;
    }

    public ArrayList<Double> getY() {
        return y;
    }

    public void setY(ArrayList<Double> y) {
        this.y = y;
    }

    public int getId() {
        return id;
    }

    public void setId(int id) {
        this.id = id;
    }
```

```java
    public String getName() {
        return name;
    }

    public void setName(String name) {
        this.name = name;
    }

}
```

SHAPEFILE READER

```java
/*
 * To change this license header, choose License Headers in Project
Properties.
 * To change this template file, choose Tools | Templates
 * and open the template in the editor.
 */

package masterproject;

import java.util.Map;
import java.util.HashMap;
import java.util.ArrayList;
import java.io.File;
import java.io.FileReader;
import java.io.IOException;

// geotools imports
import org.geotools.data.DataStore;
import org.geotools.data.DataStoreFinder;
import org.geotools.data.DataUtilities;
import org.geotools.data.simple.SimpleFeatureCollection;
import org.geotools.data.simple.SimpleFeatureIterator;
import org.geotools.data.simple.SimpleFeatureSource;
import org.opengis.feature.simple.SimpleFeature;

import au.com.bytecode.opencsv.CSVReader;
import java.util.NoSuchElementException;


/**
 *
 * @author Alina
 */
public class ShapefileReader {

    int minX = 427577;
    int minY = 3709300;
    int maxX = 444077;
    int maxY = 3730300;

    ArrayList<Node> nodes = new ArrayList();
    ArrayList<Link> links = new ArrayList();
    ArrayList<Node> dualNodes = new ArrayList();
    ArrayList<Link> dualLinks = new ArrayList();
    ArrayList<Node> nodesOrig = new ArrayList();
    ArrayList<Link> linksOrig = new ArrayList();
    ArrayList<Zone> zones = new ArrayList();
    ArrayList<Zone> dualZone = new ArrayList();
    ArrayList<Node> dualOrig = new ArrayList();
    ArrayList<Link> dualOrigLinks = new ArrayList();

    ArrayList<String> table =  new ArrayList();
```

```java
public int getMinX() {

    return this.minX;
}

public int getMaxX() {

    return this.maxX;
}

public int getMinY() {

    return this.minY;
}

public int getMaxY() {

    return this.maxY;
}

public ArrayList<Node> getNodes() {
    return nodes;
}

public void setNodes(ArrayList<Node> nodes) {
    this.nodes = nodes;
}

public ArrayList<Link> getLinks() {
    return links;
}

public void setLinks(ArrayList<Link> links) {
    this.links = links;
}

public ArrayList<Node> getNodesOrig() {
    return nodesOrig;
}

public void setNodesOrig(ArrayList<Node> nodesOrig) {
    this.nodesOrig = nodesOrig;
}

public ArrayList<Link> getLinksOrig() {
    return linksOrig;
}

public void setLinksOrig(ArrayList<Link> linksOrig) {
    this.linksOrig = linksOrig;
}

public ArrayList<Zone> getZones() {
    return zones;
}

public void setZones(ArrayList<Zone> zones) {
    this.zones = zones;
}

public ArrayList<Node> getDualNodes() {
    return dualNodes;
}

public void setDualNodes(ArrayList<Node> dualNodes) {
    this.dualNodes = dualNodes;
```

```java
    }

    public ArrayList<Link> getDualLinks() {
        return dualLinks;
    }

    public void setDualLinks(ArrayList<Link> dualLinks) {
        this.dualLinks = dualLinks;
    }

    public ArrayList<Zone> getDualZone() {
        return dualZone;
    }

    public void setDualZone(ArrayList<Zone> dualZone) {
        this.dualZone = dualZone;
    }

    public ArrayList<Node> getDualOrig() {
        return dualOrig;
    }

    public void setDualOrig(ArrayList<Node> dualOrig) {
        this.dualOrig = dualOrig;
    }

    public ArrayList<Link> getDualOrigLinks() {
        return dualOrigLinks;
    }

    public void setDualOrigLinks(ArrayList<Link> dualOrigLinks) {
        this.dualOrigLinks = dualOrigLinks;
    }

    public ArrayList<String> getTable() {
        return table;
    }

    public void setTable(ArrayList<String> table) {
        this.table = table;
    }


    public void loadFiles(String filePath, int scenario) throws
Exception {

        switch (scenario) {
            case 0:

loadFile(filePath.concat("/nodalpressure/SCHEMATICNODES_BASELINE_P_CURR
ENT.shp"), "nodesPress");

loadFile(filePath.concat("/waterage/SCHEMATICNODES_BASELINE_Q_CURRENT.s
hp"), "nodesAge");

loadFile(filePath.concat("/ORIGINALDATA/WATERNETWORK.shp"),
"linksOrig");
                loadFile(filePath.concat("/edges/network_simpID.shp"),
"linkIDs");
                loadFile(filePath.concat("/edges/BRESENHAM.shp"),
"links");
                loadFile(filePath.concat("/zoneboundary.shp"),
"zones");

loadFile(filePath.concat("/ORIGINALDATA/ZONESWITHPRESSUREVALUES/all_bli
nepre.shp"), "nodesOrigPress");
```

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```
loadFile(filePath.concat("/ORIGINALDATA/ZONESWITHQUALITYVALUES/all_blin
equa.shp"), "nodesOrigAge");

loadCSV("BASELINESCENARIODATA/SCENARIOTABLES/scenariobaseline.csv");
                    break;
               case 1:

loadFile(filePath.concat("/nodalpressure/SCHEMATICNODES_NEWPUMP_NOFIREF
LOW_PRE.shp"), "nodesPress");

loadFile(filePath.concat("/waterage/SCHEMATICNODES_NEWPUMPNOFF_Q.shp"),
"nodesAge");

loadFile(filePath.concat("/ORIGINALDATA/WATERNETWORK.shp"),
"linksOrig");
                    loadFile(filePath.concat("/edges/network_simpID.shp"),
"linkIDs");
                    loadFile(filePath.concat("/edges/BRESENHAM.shp"),
"links");
                    loadFile(filePath.concat("/zoneboundary.shp"),
"zones");

loadFile(filePath.concat("/ORIGINALDATA/ZONESWITHPRESSUREVALUES/newpump
noff_pre.shp"), "nodesOrigPress");

loadFile(filePath.concat("/ORIGINALDATA/ZONESWITHQUALITYVALUES/newpumpn
off_qua.shp"), "nodesOrigAge");

loadCSV("BASELINESCENARIODATA/SCENARIOTABLES/scenarionewpumpnofireflow.
csv");
                    break;
               case 2:

loadFile(filePath.concat("/nodalpressure/SCHEMATICNODES_NEWPUMP_FIREFLO
W_PRE.shp"), "nodesPress");

loadFile(filePath.concat("/waterage/SCHEMATICNODES_NEWPUMPWITHFF_Q_.shp
"), "nodesAge");

loadFile(filePath.concat("/ORIGINALDATA/WATERNETWORK.shp"),
"linksOrig");
                    loadFile(filePath.concat("/edges/network_simpID.shp"),
"linkIDs");
                    loadFile(filePath.concat("/edges/BRESENHAM.shp"),
"links");
                    loadFile(filePath.concat("/zoneboundary.shp"),
"zones");

loadFile(filePath.concat("/ORIGINALDATA/ZONESWITHPRESSUREVALUES/newpump
fireflow_pre.shp"), "nodesOrigPress");

loadFile(filePath.concat("/ORIGINALDATA/ZONESWITHQUALITYVALUES/newpumpf
ireflow_qua.shp"), "nodesOrigAge");

loadCSV("BASELINESCENARIODATA/SCENARIOTABLES/scenarionewpumpwithfireflo
w.csv");
                    break;
               case 3:

loadFile(filePath.concat("/DUAL_NON_POT/nodalpressure/SCHEMATICNODES_DU
AL_NONPOT_PRE.shp"), "nodesPress");

loadFile(filePath.concat("/DUAL_NON_POT/waterage/SCHEMATICNODES_DUAL_NO
NPOT_Q.shp"), "nodesAge");
```

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```
loadFile(filePath.concat("/DUAL_NON_POT/ORIGINALDATA/WATERNETWORK.shp")
, "linksOrig");

loadFile(filePath.concat("/DUAL_NON_POT/edges/network_simpID.shp"),
"linkIDs");

loadFile(filePath.concat("/DUAL_NON_POT/edges/BRESENHAM.shp"),
"links");

loadFile(filePath.concat("/DUAL_NON_POT/zoneboundary.shp"), "zones");

loadFile(filePath.concat("/DUAL_NON_POT/ORIGINALDATA/ZONESWITHPRESSUREV
ALUES/dualnonpot_pre.shp"), "nodesOrigPress");

loadFile(filePath.concat("/DUAL_NON_POT/ORIGINALDATA/ZONESWITHQUALITYVA
LUES/dualnonpot_qua.shp"), "nodesOrigAge");
                loadFile(filePath.concat("/dualbresenham.shp"),
"linksDual");

loadFile(filePath.concat("/DUAL_NON_POT/nodalpressure/DUAL_NONPOTABLE_S
CORES_PRE.shp"), "nodesDualPress");
                loadFile(filePath.concat("/dualWDSboundry.shp"),
"zoneDual");

loadFile(filePath.concat("/DUAL_NON_POT/waterage/DUAL_NONPOTABLE_SCORES
_QUA.shp"), "nodesDualAge");
                loadFile(filePath.concat("/dualrealnetwork.shp"),
"dualOrig");

loadFile(filePath.concat("/DUAL_NON_POT/ORIGINALDATA/DUAL/dualnonpotabl
e_pre.shp"), "dualOrigPre");

loadFile(filePath.concat("/DUAL_NON_POT/ORIGINALDATA/DUAL/dualnonpotabl
e_qua.shp"), "dualOrigAge");

loadCSV("BASELINESCENARIODATA/SCENARIOTABLES/Scenariooption_DUAL_NON_PO
T_A.csv");
                break;
            case 4:

loadFile(filePath.concat("/DUAL_OUTDOOR_ONLY/nodalpressure/SCHEMATICNOD
ES_DUAL_OUTDOOR_PRE.shp"), "nodesPress");

loadFile(filePath.concat("/DUAL_OUTDOOR_ONLY/waterage/SCHEMATICNODES_DU
AL_OUTDOOR_Q.shp"), "nodesAge");

loadFile(filePath.concat("/DUAL_OUTDOOR_ONLY/ORIGINALDATA/WATERNETWORK.
shp"), "linksOrig");

loadFile(filePath.concat("/DUAL_OUTDOOR_ONLY/edges/network_simpID.shp")
, "linkIDs");

loadFile(filePath.concat("/DUAL_OUTDOOR_ONLY/edges/BRESENHAM.shp"),
"links");

loadFile(filePath.concat("/DUAL_OUTDOOR_ONLY/zoneboundary.shp"),
"zones");

loadFile(filePath.concat("/DUAL_OUTDOOR_ONLY/ORIGINALDATA/ZONESWITHPRES
SUREVALUES/dualoutdooronly_pre.shp"), "nodesOrigPress");

loadFile(filePath.concat("/DUAL_OUTDOOR_ONLY/ORIGINALDATA/ZONESWITHQUAL
ITYVALUES/dualoutdoor_qua.shp"), "nodesOrigAge");
                loadFile(filePath.concat("/dualbresenham.shp"),
"linksDual");
```

```
loadFile(filePath.concat("/DUAL_OUTDOOR_ONLY/nodalpressure/DUAL_OUTDOOR
ONLY_SCORES_PRE.shp"), "nodesDualPress");
                loadFile(filePath.concat("/dualWDSboundry.shp"),
"zoneDual");

loadFile(filePath.concat("/DUAL_OUTDOOR_ONLY/waterage/DUAL_OUTDOORONLY_
SCORES_QUA.shp"), "nodesDualAge");
                loadFile(filePath.concat("/dualrealnetwork.shp"),
"dualOrig");

loadFile(filePath.concat("/DUAL_OUTDOOR_ONLY/ORIGINALDATA/DUAL/dualoutd
ooronly_pre.shp"), "dualOrigPre");

loadFile(filePath.concat("/DUAL_OUTDOOR_ONLY/ORIGINALDATA/DUAL/dualoutd
ooronly_qua.shp"), "dualOrigAge");

loadCSV("BASELINESCENARIODATA/SCENARIOTABLES/scenarioptionB_DUAL_OUTDOO
R_ONLY.csv");
                break;
            case 5:

loadFile(filePath.concat("/HYBRID_NONPOTABLE/nodalpressure/SCHEMATICNOD
ES_HYBRID_NONPOT_PRE.shp"), "nodesPress");

loadFile(filePath.concat("/HYBRID_NONPOTABLE/waterage/SCHEMATICNODES_HY
BRIDNONPOT_Q.shp"), "nodesAge");

loadFile(filePath.concat("/HYBRID_NONPOTABLE/ORIGINALDATA/WATERNETWORK.
shp"), "linksOrig");

loadFile(filePath.concat("/HYBRID_NONPOTABLE/edges/network_simpID.shp")
, "linkIDs");

loadFile(filePath.concat("/HYBRID_NONPOTABLE/edges/BRESENHAM.shp"),
"links");

loadFile(filePath.concat("/HYBRID_NONPOTABLE/zoneboundary.shp"),
"zones");

loadFile(filePath.concat("/HYBRID_NONPOTABLE/ORIGINALDATA/ZONESWITHPRES
SUREVALUES/hybridnonpot_pre.shp"), "nodesOrigPress");

loadFile(filePath.concat("/HYBRID_NONPOTABLE/ORIGINALDATA/ZONESWITHQUAL
ITYVALUES/hybridnonpot_qua.shp"), "nodesOrigAge");
                loadFile(filePath.concat("/dualbresenham.shp"),
"linksDual");

loadFile(filePath.concat("/HYBRID_NONPOTABLE/nodalpressure/HYBRIDNONPOT
ABLESCORES_PRE.shp"), "nodesDualPress");
                loadFile(filePath.concat("/dualWDSboundry.shp"),
"zoneDual");

loadFile(filePath.concat("/HYBRID_NONPOTABLE/waterage/HYBRID_NONPOTABLE
_SCORES_Qua.shp"), "nodesDualAge");
                loadFile(filePath.concat("/dualrealnetwork.shp"),
"dualOrig");

loadFile(filePath.concat("/HYBRID_NONPOTABLE/ORIGINALDATA/dual/hybridno
npotable_pre.shp"), "dualOrigPre");

loadFile(filePath.concat("/HYBRID_NONPOTABLE/ORIGINALDATA/dual/hybridno
npotable_qua.shp"), "dualOrigAge");

loadCSV("BASELINESCENARIODATA/SCENARIOTABLES/scenarioption_c_HYBRID_NON
POTABLE.csv");
```

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```
                    break;
                case 6:

loadFile(filePath.concat("/HYBRID_OUTDOOR_ONLY/nodalpressure/SCHEMATICN
ODES_HYBRIDOUTDOOR_PRE.shp"), "nodesPress");

loadFile(filePath.concat("/HYBRID_OUTDOOR_ONLY/waterage/SCHEMATICNODES_
HYBRIDOUTDOOR_Q.shp"), "nodesAge");

loadFile(filePath.concat("/HYBRID_OUTDOOR_ONLY/ORIGINALDATA/WATERNETWOR
K.shp"), "linksOrig");

loadFile(filePath.concat("/HYBRID_OUTDOOR_ONLY/edges/network_simpID.shp
"), "linkIDs");

loadFile(filePath.concat("/HYBRID_OUTDOOR_ONLY/edges/BRESENHAM.shp"),
"links");

loadFile(filePath.concat("/HYBRID_OUTDOOR_ONLY/zoneboundary.shp"),
"zones");

loadFile(filePath.concat("/HYBRID_OUTDOOR_ONLY/ORIGINALDATA/ZONESWITHPR
ESSUREVALUES/hybridoutdoor_pre.shp"), "nodesOrigPress");

loadFile(filePath.concat("/HYBRID_OUTDOOR_ONLY/ORIGINALDATA/ZONESWITHQU
ALITYVALUES/hybridoutdoor_qua.shp"), "nodesOrigAge");
                loadFile(filePath.concat("/dualbresenham.shp"),
"linksDual");

loadFile(filePath.concat("/HYBRID_OUTDOOR_ONLY/nodalpressure/HYBRID_OUT
DOORONLY_SCORES_PRE.shp"), "nodesDualPress");
                loadFile(filePath.concat("/dualWDSboundry.shp"),
"zoneDual");

loadFile(filePath.concat("/HYBRID_OUTDOOR_ONLY/waterage/HYBRID_OUTDOORO
NLY_SCORES_QUA.shp"), "nodesDualAge");
                loadFile(filePath.concat("/dualrealnetwork.shp"),
"dualOrig");

loadFile(filePath.concat("/HYBRID_OUTDOOR_ONLY/ORIGINALDATA/DUAL/hybrid
outdooronly_pre.shp"), "dualOrigPre");

loadFile(filePath.concat("/HYBRID_OUTDOOR_ONLY/ORIGINALDATA/DUAL/hybrid
outdooronly_qua.shp"), "dualOrigAge");

loadCSV("BASELINESCENARIODATA/SCENARIOTABLES/scenarioption_D_HYBRID_OUT
DOOR_ONLY.csv");
                break;
        }

    }

    public void loadCSV(String fileName) throws IOException {

        try {
            CSVReader reader = new CSVReader(new FileReader(fileName),
';');
            String[] read;
            /*
            ignore blank lines and the title
            */
            while ((read = reader.readNext()) != null) {
                if (read[1].length() != 0 && !read[1].contains("SI")) {
                    table.add(read[0]);
                    table.add(read[1]);
                    if (read[2].length() != 0) {
```

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```
                                table.add(read[2]);
                            }
                        }
                    }
                } catch (IOException e) {
                    System.out.println("Error occured while reading csv: " +
e.toString());
                }
        }

    public void loadFile(String fileName, String mode) throws Exception
{

            File file = new File(fileName);
            Map connect = new HashMap();
            connect.put("url", DataUtilities.fileToURL(file));
            DataStore dataStore = DataStoreFinder.getDataStore(connect);
            String[] typeNames = dataStore.getTypeNames();
            String typeName = typeNames[0];

            SimpleFeatureSource source =
dataStore.getFeatureSource(typeName);
            SimpleFeatureCollection collection = source.getFeatures();
            SimpleFeatureIterator iterator = collection.features();

            String read;
            String[] coordinates;
            SimpleFeature current;

            try {
                while (iterator.hasNext()) {

                    /*
                    extracting geometry only, stays the same for every item
                    */
                    current = iterator.next();
                    read =
current.getDefaultGeometryProperty().getValue().toString().trim();
                    if (read.startsWith("MULTILINESTRING")) {
                        read = read.substring(18, read.length()-3);
                    } else if (read.startsWith("POINT")) {
                        read = read.substring(7, read.length()-2);
                    } else if (read.startsWith("MULTIPOLYGON")) {
                        read = read.substring(16, read.length()-4);
                    }
                    coordinates = read.split(", | ");
                    Link link;
                    Node node;
                    Zone zone;

                    /*
                    Collecting information for node, zone, and link
containers.
                    Simple nodes save the pressure/water age values of
their original nodes for the graph.
                    */
                    switch (mode) {
                        case "links" :
                            link = new Link();
                            for (int i = 0; i < coordinates.length; i++) {
                                if (i % 2 == 0) {

link.getX().add(Double.parseDouble(coordinates[i]));
                                } else {

link.getY().add(Double.parseDouble(coordinates[i]));
```

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```java
                            }
                        }
                        this.links.add(link);
                        break;
                    case "linksOrig" :
                        link = new Link();
                        for (int i = 0; i < coordinates.length; i++) {
                            if (i % 2 == 0) {

link.getX().add(Double.parseDouble(coordinates[i]));
                            } else {

link.getY().add(Double.parseDouble(coordinates[i]));
                            }
                        }

link.setId(Integer.parseInt(current.getAttribute("epa_id").toString()))
;
                        this.linksOrig.add(link);
                        break;
                    case "linkIDs" :
                        for (Link l : this.linksOrig) {
                            if (l.getId() ==
Integer.parseInt(current.getAttribute("epa_id").toString())) {

l.setSimpleID(Integer.parseInt(current.getAttribute("simpleID").toStrin
g()));
                                break;
                            }
                        }
                        break;
                    case "nodesPress" :
                        node = new Node();
                        node.setX(Double.parseDouble(coordinates[0]));
                        node.setY(Double.parseDouble(coordinates[1]));
                        node.setSimpleID((int)
Double.parseDouble(current.getAttribute("simple_ID_").toString()));
                        for (int i = 96; i < 120; i++) {
                            node.getSatPressure()[i-96] =
Double.parseDouble(current.getAttribute("hour"+ String.valueOf(i)
+"1").toString());
                        }
                        node.setTotal(node.getSatPressure()[0] +
Double.parseDouble(current.getAttribute("hour960").toString()));
                        node.calcPressGrad();
                        this.nodes.add(node);
                        break;
                    case "nodesOrigPress" :
                        node = new Node();
                        node.setX(Double.parseDouble(coordinates[0]));
                        node.setY(Double.parseDouble(coordinates[1]));

node.setId(current.getAttribute("epa_id").toString());

node.setSimpleID(Integer.parseInt(current.getAttribute("simple").toStri
ng()));

node.setZoneId(current.getAttribute("ZoneID").toString());
                        for (int i = 96; i < 120; i++) {
                            node.getSatPressure()[i-96] =
Double.parseDouble(current.getAttribute("PR"+
String.valueOf(i)).toString());
                        }
                        for (Node n : this.nodes) {
                            if (n.getSimpleID() == (int)
Double.parseDouble(current.getAttribute("simple").toString())) {
```

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                                n.getPre().add(node.getSatPressure());
                                n.getPreIds().add(node.getId());
                                break;
                            }
                        }
                        this.nodesOrig.add(node);
                        break;
                    case "nodesAge" :
                        for (Node n : this.nodes) {
                            if (n.getSimpleID() == (int)
Double.parseDouble(current.getAttribute("simple_ID_").toString())) {
                                for (int i = 96; i < 120; i++) {
                                    n.getSatAge()[i-96] =
Double.parseDouble(current.getAttribute("Q_1_"+
String.valueOf(i)).toString());
                                }
                                break;
                            }
                        }
                        break;
                    case "nodesOrigAge" :
                        for (Node n : this.nodesOrig) {
                            if
(n.getId().contains(current.getAttribute("epa_id").toString())) {
                                for (int i = 96; i < 120; i++) {
                                    n.getSatAge()[i-96] =
Double.parseDouble(current.getAttribute("q"+
String.valueOf(i)).toString());
                                }
                                for (Node n2 : this.nodes) {
                                    if (n2.getSimpleID() ==
n.getSimpleID()) {

                                        n2.getQua().add(n.getSatAge());
                                        n2.getQuaIds().add(n.getId());
                                        break;
                                    }
                                }
                            }
                        }
                        break;
                    case "zones" :
                        zone = new Zone();
                        for (int i = 0; i < coordinates.length; i++) {
                            if (i % 2 == 0) {

zone.getX().add(Double.parseDouble(coordinates[i]));
                            } else {

zone.getY().add(Double.parseDouble(coordinates[i]));
                            }
                        }

zone.setId(Integer.parseInt(current.getAttribute("zone").toString().sub
string(5)));

zone.setName(current.getAttribute("zone").toString());
                        this.zones.add(zone);
                        break;
                    case "linksDual" :
                        link = new Link();
                        for (int i = 0; i < coordinates.length; i++) {
                            if (i % 2 == 0) {

link.getX().add(Double.parseDouble(coordinates[i]));
                            } else {
```

```java
link.getY().add(Double.parseDouble(coordinates[i]));
                    }
                }
                this.dualLinks.add(link);
                break;
            case "nodesDualPress" :
                node = new Node();
                node.setX(Double.parseDouble(coordinates[0]));
                node.setY(Double.parseDouble(coordinates[1]));
                node.setSimpleID((int)
Double.parseDouble(current.getAttribute("simple_ID_").toString()));
                for (int i = 96; i < 120; i++) {
                    node.getSatPressure()[i-96] =
Double.parseDouble(current.getAttribute("hour"+ String.valueOf(i)
+"1").toString());
                }
                node.setTotal(node.getSatPressure()[0] +
Double.parseDouble(current.getAttribute("hour960").toString()));
                node.calcPressGrad();
                this.dualNodes.add(node);
                break;
            case "nodesDualAge" :
                for (Node n : this.dualNodes) {
                    if (n.getSimpleID() == (int)
Double.parseDouble(current.getAttribute("simple_ID_").toString())) {
                        for (int i = 96; i < 120; i++) {
                            n.getSatAge()[i-96] =
Double.parseDouble(current.getAttribute("Q_1_"+
String.valueOf(i)).toString());
                        }
                        break;
                    }
                }
                break;
            case "zoneDual" :
                zone = new Zone();
                for (int i = 0; i < coordinates.length; i++) {
                    if (i % 2 == 0) {

zone.getX().add(Double.parseDouble(coordinates[i]));
                    } else {

zone.getY().add(Double.parseDouble(coordinates[i]));
                    }
                }
                this.dualZone.add(zone);
                break;
            case "dualOrigPre" :
                node = new Node();
                node.setX(Double.parseDouble(coordinates[0]));
                node.setY(Double.parseDouble(coordinates[1]));

node.setId(current.getAttribute("epa_id").toString());

node.setSimpleID(Integer.parseInt(current.getAttribute("simple").toStri
ng()));
                for (int i = 96; i < 120; i++) {
                    node.getSatPressure()[i-96] =
Double.parseDouble(current.getAttribute("PR"+
String.valueOf(i)).toString());
                }
                for (Node n : this.dualNodes) {
                    if (n.getSimpleID() == (int)
Double.parseDouble(current.getAttribute("simple").toString())) {
                        n.getPre().add(node.getSatPressure());
```

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```java
                                                n.getPreIds().add(node.getId());
                                                break;
                                        }
                                }
                                this.dualOrig.add(node);
                                break;
                        case "dualOrigAge" :
                                for (Node n : this.dualOrig) {
                                        if
(n.getId().contains(current.getAttribute("epa_id").toString())) {
                                                for (int i = 96; i < 120; i++) {
                                                        n.getSatAge()[i-96] =
Double.parseDouble(current.getAttribute("q"+
String.valueOf(i)).toString());
                                                }
                                                for (Node n2 : this.dualNodes) {
                                                        if (n2.getSimpleID() ==
n.getSimpleID()) {

                                                                n2.getQua().add(n.getSatAge());
                                                                n2.getQuaIds().add(n.getId());
                                                                break;
                                                        }
                                                }
                                        }
                                }
                                break;
                        case "dualOrig" :
                                link = new Link();
                                for (int i = 0; i < coordinates.length; i++) {
                                        if (i % 2 == 0) {

link.getX().add(Double.parseDouble(coordinates[i]));
                                        } else {

link.getY().add(Double.parseDouble(coordinates[i]));
                                        }
                                }

link.setId(Integer.parseInt(current.getAttribute("epa_id_dua").toString
()));
                                String simple =
current.getAttribute("simpleID").toString();
                                link.setSimpleID(Integer.parseInt(simple));
                                this.dualOrigLinks.add(link);
                                break;
                    }

            }
        } catch (NumberFormatException | NoSuchElementException e) {
            System.out.println("Error occured while reading shapefile:
" + e.toString());
        }
    }
}
```

PROJECT

```java
/*
 * To change this template, choose Tools | Templates
 * and open the template in the editor.
 */
package masterproject;

import javafx.application.Application;
import javafx.scene.Scene;
```

```java
import javafx.scene.canvas.Canvas;
import javafx.scene.canvas.GraphicsContext;
import javafx.scene.paint.Color;
import javafx.scene.shape.Arc;
import javafx.scene.shape.ArcType;
import javafx.scene.shape.Polyline;
import javafx.stage.Stage;

import javafx.scene.layout.AnchorPane;
import javafx.scene.chart.LineChart;
import javafx.scene.chart.NumberAxis;
import javafx.scene.chart.XYChart;
import javafx.scene.control.ScrollPane;
import javafx.scene.control.ChoiceBox;
import javafx.scene.control.ToggleGroup;
import javafx.scene.control.Toggle;
import javafx.scene.control.RadioButton;
import javafx.scene.control.Separator;
import javafx.scene.control.CheckBox;
import javafx.scene.control.Label;
import javafx.scene.control.Button;
import javafx.scene.control.Slider;
import javafx.scene.control.TableColumn;
import javafx.scene.control.TableView;
import javafx.scene.control.cell.PropertyValueFactory;
import javafx.scene.image.Image;
import javafx.scene.image.ImageView;
import javafx.scene.input.MouseEvent;
import javafx.event.EventHandler;
import javafx.beans.property.SimpleStringProperty;
import javafx.beans.value.ObservableValue;
import javafx.beans.value.ChangeListener;

import java.util.ArrayList;
import javafx.collections.FXCollections;
import javafx.collections.ObservableList;
import javafx.event.ActionEvent;

/**
 *
 * @author Alina
 */
public class Masterproject extends Application {

    int scenario = 0;
    boolean selectMode = true;
    int simpleID = -1;
    double scale = 1.0;

    double pressedX;
    double pressedY;

    ShapefileReader[] readers = new ShapefileReader[7];

    ArrayList<Arc> arcs = new ArrayList();
    ArrayList<Arc> origArcs = new ArrayList();
    ArrayList<Polyline> origLinks = new ArrayList();

    AnchorPane window = new AnchorPane();
    LineChart<Number, Number> graph;

    ArrayList<String> Ids = new ArrayList();
    Color[] lineChartColors = {Color.web("#f9d900"),
Color.web("#a9e200"), Color.web("#22bad9"), Color.web("#0181e2"),
        Color.web("#2f357f"), Color.web("#860061"),
Color.web("#c62b00"), Color.web("#ff5700")};
```

```
    Canvas canOrigLinks;
    Canvas canOrig;
    GraphicsContext conOrigLinks;
    GraphicsContext conOrig;

    /**
     *
     * Projects points from one coordinate system to another one.
     * @param range Value range of the canvas in direction of x-axis or
y-axis.
     * @param point Point in 1D to scale.
     * @param min Minimal value in original coordinate system.
     * @param max Maximal value in original coordinate system.
     * @param orient Needed for adjusting the orientation for the y-
Axis when scaling original coordinates.
     * @return Point in 1D in new coordinate system.
     */
    public double scaleCoordinates(double range, double point, int min,
int max, int orient) {

        double rangeOrig = max - min;
        double result = -1;

        double coeff = range/rangeOrig;
        switch(orient) {
            case 0:
                result = (Math.abs(point - min)*coeff);
                break;
            case 1:
                result = (Math.abs(point - max)*coeff);
                break;
        }

        return result;
    }

    /**
     *
     * @param context GraphicsContext to draw on.
     * @param reader ShapefileReader with scenario data to draw.
     * @param mode Describes drawing mode as a value. 0 equals links
for multiple map view, 1 for original data links.
     * @param offsetX For calculating the links' necessary offset in
direction of the x-axis in the multiple map view.
     * @param offsetY For calculating the links' necessary offset in
direction of the y.axis in the multiple map view.
     * @param range Only needed for multiple map view. Indicates number
of maps on canvas.
     */
    public void drawLinks(GraphicsContext context, ShapefileReader
reader, int mode, double offsetX, double offsetY, int[] range) {

        double[] x;
        double[] y;
        context.setStroke(Color.BLACK);
        double offX;
        double offY = 0;
        int step = 0;
        int max = range[1] - range[0];

        context.clearRect(0, 0, context.getCanvas().getWidth(),
context.getCanvas().getHeight());
        switch (mode) {
            case 0 :
                while (offY < 730) {
```

```
                        offX = 0;
                        while (offX < 910 && step <= max) {
                            for (Link link : reader.getLinks()) {
                                x = new double[link.getX().size()];
                                y = new double[link.getY().size()];
                                for (int i = 0; i < link.getX().size();
i++) {
                                    x[i] = scaleCoordinates(offsetX,
link.getX().get(i), reader.getMinX(), reader.getMaxX(), 0) + offX;
                                    y[i] = scaleCoordinates(offsetY,
link.getY().get(i), reader.getMinY(), reader.getMaxY(), 1) + offY;
                                }
                                context.strokePolyline(x, y,
link.getX().size());
                            }
                            for (Link link : reader.getDualLinks()) {
                                x = new double[link.getX().size()];
                                y = new double[link.getY().size()];
                                for (int i = 0; i < link.getX().size();
i++) {
                                    x[i] = scaleCoordinates(offsetX,
link.getX().get(i), reader.getMinX(), reader.getMaxX(), 0) + offX -
100;
                                    y[i] = scaleCoordinates(offsetY,
link.getY().get(i), reader.getMinY(), reader.getMaxY(), 1) + offY;
                                }
                                context.strokePolyline(x, y,
link.getX().size());
                            }
                            offX += offsetX;
                            step++;
                        }
                        offY += offsetY;
                    }
                    break;
                case 1 :
                    origLinks.clear();
                    if (scale > 2) {
                        context.setLineWidth(0.2);
                    } else {
                        context.setLineWidth(1);
                    }
                    for (Link link : reader.getLinksOrig()) {
                        final Polyline line = new Polyline();
                        line.setId(Integer.toString(link.getSimpleID()));
                        line.setStroke(Color.BLACK);
                        line.setOpacity(0);

                        if (link.getSimpleID() == simpleID) {
                            context.setStroke(Color.YELLOW);
                        } else {
                            context.setStroke(Color.BLACK);
                        }

                        x = new double[link.getX().size()];
                        y = new double[link.getY().size()];
                        for (int i = 0; i < link.getX().size(); i++) {
                            line.getPoints().add(scaleCoordinates(offsetX,
link.getX().get(i), reader.getMinX(), reader.getMaxX(), 0) +
context.getCanvas().getLayoutX());
                            line.getPoints().add(scaleCoordinates(offsetY,
link.getY().get(i), reader.getMinY() - 1000, reader.getMaxY() + 10000,
1) + context.getCanvas().getLayoutY());
                            x[i] = scaleCoordinates(offsetX,
link.getX().get(i), reader.getMinX(), reader.getMaxX(), 0);
```

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                            y[i] = scaleCoordinates(offsetY,
link.getY().get(i), reader.getMinY() - 1000, reader.getMaxY()+10000,
1);
                        }
                        this.origLinks.add(line);
                        context.strokePolyline(x, y, link.getX().size());
                    }
                    for (Link link : reader.getDualOrigLinks()) {
                        final Polyline line = new Polyline();
                        line.setId(Integer.toString(link.getSimpleID()));
                        line.setStroke(Color.BLACK);
                        line.setOpacity(0);

                        if (link.getSimpleID() == simpleID) {
                            context.setStroke(Color.YELLOW);
                        } else {
                            context.setStroke(Color.BLACK);
                        }

                        /*
                         * offset of 40 for dual links to avoid overlap
                         */
                        x = new double[link.getX().size()];
                        y = new double[link.getY().size()];
                        for (int i = 0; i < link.getX().size(); i++) {
                            line.getPoints().add(scaleCoordinates(208,
link.getX().get(i), reader.getMinX(), reader.getMaxX(), 0) +
context.getCanvas().getLayoutX() - 40);
                            line.getPoints().add(scaleCoordinates(380,
link.getY().get(i), reader.getMinY() - 1000, reader.getMaxY() + 10000,
1) + context.getCanvas().getLayoutY());
                            x[i] = scaleCoordinates(208,
link.getX().get(i), reader.getMinX(), reader.getMaxX(), 0) - 40;
                            y[i] = scaleCoordinates(380,
link.getY().get(i), reader.getMinY() - 1000, reader.getMaxY()+10000,
1);
                        }
                        this.origLinks.add(line);
                        context.strokePolyline(x, y, link.getX().size());
                    }
                    break;
            }
        }
    }

    /**
     *
     * @param context GraphicsContext to draw on.
     * @param reader ShapefileReader with scenario data to draw.
     * @param mode Describes drawing mode as a String value.
     * @param offsetX For calculating the nodes' necessary offset in
direction of the x-axis in the multiple map view.
     * @param offsetY For calculating the nodes' necessary offset in
direction of the y.axis in the multiple map view.
     * @param range Only needed for multiple map view. Indicates number
of maps on canvas.
     */
    public void drawNodes(GraphicsContext context, ShapefileReader
reader, String mode, double offsetX, double offsetY, int[] range) {

        double x;
        double y;
        double ang;
        double offX;
        double offY = 0;
        int step = range[0];
```

```
        switch (mode) {
            case "press":
                this.arcs.clear();
                context.clearRect(0, 0, context.getCanvas().getWidth(),
context.getCanvas().getHeight());
                while (offY < 730) {
                    offX = 0;
                    while (offX < 910 && step <= range[1]) {
                        for (final Node node : reader.getNodes()) {
                            /*
                            clickable nodes in the view remaining
invisible
                            */
                            final Arc arc = new Arc();

arc.setId(Integer.toString(node.getSimpleID()));
                            arc.setFill(Color.WHITE);
                            context.setStroke(Color.BLACK);
                            context.setFill(Color.GOLD);
                            context.setLineWidth(0.5);
                            x = scaleCoordinates(offsetX, node.getX(),
reader.getMinX(), reader.getMaxX(), 0) - 4 + offX;
                            y = scaleCoordinates(offsetY, node.getY(),
reader.getMinY(), reader.getMaxY(), 1) - 4 + offY;

                            arc.setCenterX(x +
context.getCanvas().getLayoutX() + 4);
                            arc.setCenterY(y +
context.getCanvas().getLayoutY() + 4);
                            arc.setRadiusX(8);
                            arc.setRadiusY(8);
                            arc.setStartAngle(0);
                            arc.setLength(360);
                            arc.setType(ArcType.ROUND);
                            arc.setOpacity(0);

                            /*
                            drawing circle view
                            */
                            ang =
node.getSatPressure()[step+1]/node.getTotal();

                            context.fillArc((x-4), (y-4), 16, 16, 0,
360*(1-ang), ArcType.ROUND);
                            context.strokeArc((x-4), (y-4), 16, 16, 0,
360*(1-ang), (ang == 0 || ang == 1) ? ArcType.OPEN : ArcType.ROUND);
                            context.setStroke(Color.WHITE);
                            context.setFill(Color.NAVY);
                            context.fillArc((x-4), (y-4), 16, 16,
360*(1-ang), 360*ang, ArcType.ROUND);
                            context.strokeArc((x-4), (y-4), 16, 16,
360*(1-ang), 360*ang, (ang == 0 || ang == 1) ? ArcType.OPEN :
ArcType.ROUND);

                            context.setStroke(Color.BLACK);
                            context.setFill(Color.GOLD);
                            context.setLineWidth(1);
                            ang =
node.getSatPressure()[step]/node.getTotal();
                            context.fillArc(x, y, 8, 8, 0, 360*(1-ang),
ArcType.ROUND);
                            context.strokeArc(x, y, 8, 8, 0, 360*(1-
ang), (ang == 0 || ang == 1) ? ArcType.OPEN : ArcType.ROUND);
                            context.setStroke(Color.WHITE);
                            context.setFill(Color.NAVY);
```

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                                context.fillArc(x, y, 8, 8, 360*(1-ang),
360*ang, ArcType.ROUND);
                                context.strokeArc(x, y, 8, 8, 360*(1-ang),
360*ang, (ang == 0 || ang == 1) ? ArcType.OPEN : ArcType.ROUND);


arc.addEventHandler(MouseEvent.MOUSE_CLICKED, new
EventHandler<MouseEvent>() {
                                @Override public void handle(MouseEvent
e) {
                                    /*
                                    bounds for zoom mode
                                    */
                                    double minX = Double.MAX_VALUE;
                                    double minY = Double.MAX_VALUE;
                                    double maxY = -1;

                                    /*
                                    filling graph
                                    */
                                    graph.getData().clear();
                                    for (double[] array :
node.getPre()) {
                                        XYChart.Series series = new
XYChart.Series();
                                        int step = 96;
                                        series.setName("Node " +
Integer.toString(node.getSimpleID()));
                                        Ids = node.getPreIds();
                                        for (double d : array) {
                                            series.getData().add(new
XYChart.Data(step, d));
                                            step++;
                                        }
                                        graph.getData().add(series);
                                    }
                                    for (Arc a: origArcs) {
                                        if (Integer.parseInt(a.getId())
== Integer.parseInt(arc.getId())) {
                                            if (minX > a.getCenterX() -
conOrig.getCanvas().getLayoutX()) {
                                                minX = a.getCenterX() -
conOrig.getCanvas().getLayoutX();
                                            }
                                            if (minY > a.getCenterY() -
conOrig.getCanvas().getLayoutY()) {
                                                minY = a.getCenterY() -
conOrig.getCanvas().getLayoutY();
                                            }
                                            if (maxY < a.getCenterY() -
conOrig.getCanvas().getLayoutY()) {
                                                maxY = a.getCenterY() -
conOrig.getCanvas().getLayoutY();
                                            }
                                        }
                                    }
                                    for (Polyline p: origLinks) {
                                        if (Integer.parseInt(p.getId())
== Integer.parseInt(arc.getId())) {
                                            if (minX >
p.getPoints().get(0) - conOrigLinks.getCanvas().getLayoutX()) {
                                                minX =
p.getPoints().get(0) - conOrigLinks.getCanvas().getLayoutX();
                                            }
                                            if (minY >
p.getPoints().get(1) - conOrigLinks.getCanvas().getLayoutY()) {
```

```
                                            minY =
p.getPoints().get(1) - conOrigLinks.getCanvas().getLayoutY();
                                        }
                                        if (maxY <
p.getPoints().get(1) - conOrigLinks.getCanvas().getLayoutY()) {
                                            maxY =
p.getPoints().get(1) - conOrigLinks.getCanvas().getLayoutY();
                                        }
                                        if (minX >
p.getPoints().get(2) - conOrigLinks.getCanvas().getLayoutX()) {
                                            minX =
p.getPoints().get(2) - conOrigLinks.getCanvas().getLayoutX();
                                        }
                                        if (minY >
p.getPoints().get(3) - conOrigLinks.getCanvas().getLayoutY()) {
                                            minY =
p.getPoints().get(3) - conOrigLinks.getCanvas().getLayoutY();
                                        }
                                        if (maxY <
p.getPoints().get(3) - conOrigLinks.getCanvas().getLayoutY()) {
                                            maxY =
p.getPoints().get(3) - conOrigLinks.getCanvas().getLayoutY();
                                        }
                                    }
                                }
                                /*
                                 * simpleID determines which links
and nodes have to be highlighted after zooming
                                 */
                                simpleID =
Integer.parseInt(arc.getId());

                                int[] range = {0, 0};

                                conOrig.translate(-
conOrig.getTransform().getTx(), -conOrig.getTransform().getTy());
                                conOrigLinks.translate(-
conOrigLinks.getTransform().getTx(), -
conOrigLinks.getTransform().getTy());
                                conOrigLinks.clearRect(0, 0, 208,
380);
                                conOrig.clearRect(0, 0, 208, 380);
                                if (selectMode) {
                                    /*
                                     * simpleID determines which
links and nodes have to be highlighted after zooming
                                     */
                                    double zoomRange = (maxY - minY
+ 4);
                                    /*
                                     * zoomRange adapts to size of
the zoomed extend dependent on its ratio to original canvas' extend
                                     */
                                    if (zoomRange < 0.25*(208-
0/380.0)) {

                                        scale = 8.0;
                                    } else {
                                        scale = 2.0;
                                    }

                                    conOrigLinks.translate(-
(scale*minX - scale*6), -(scale*minY - scale*6));
                                    conOrigLinks.scale(scale,
scale);
                                    conOrig.translate(-(scale*minX
- scale*6), -(scale*minY - scale*6));
```

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```
                                                conOrig.scale(scale, scale);
                                        }
                                        drawLinks(conOrigLinks,
readers[scenario], 1, 208, 380, range);
                                        drawNodes(conOrig,
readers[scenario], "orig", 208, 380, range);
                                        if (selectMode) {
                                                conOrigLinks.scale(1.0/scale,
1.0/scale);
                                                conOrig.scale(1.0/scale,
1.0/scale);
                                        }
                                }
                        });
                        this.arcs.add(arc);
                }
                /*
                dual extend; most functions remain the same
                */
                for (final Node node : reader.getDualNodes()) {
                        final Arc arc = new Arc();

arc.setId(Integer.toString(node.getSimpleID()));
                        arc.setFill(Color.WHITE);
                        context.setStroke(Color.WHITE);
                        context.setFill(Color.RED);
                        context.setLineWidth(0.5);
                        x = scaleCoordinates(offsetX, node.getX(),
reader.getMinX(), reader.getMaxX(), 0) - 4 + offX - 100;
                        y = scaleCoordinates(offsetY, node.getY(),
reader.getMinY(), reader.getMaxY(), 1) - 4 + offY;

                        arc.setCenterX(x +
context.getCanvas().getLayoutX() + 4);
                        arc.setCenterY(y +
context.getCanvas().getLayoutY() + 4);
                        arc.setRadiusX(8);
                        arc.setRadiusY(8);
                        arc.setStartAngle(0);
                        arc.setLength(360);
                        arc.setType(ArcType.ROUND);
                        arc.setOpacity(0);

                        ang =
node.satPressure[step+1]/node.getTotal();

                        context.fillArc((x-4), (y-4), 16, 16, 0,
360*(1-ang), ArcType.ROUND);
                        context.strokeArc((x-4), (y-4), 16, 16, 0,
360*(1-ang), (ang == 0 || ang == 1) ? ArcType.OPEN : ArcType.ROUND);
                        context.setStroke(Color.WHITE);
                        context.setFill(Color.GREEN);
                        context.fillArc((x-4), (y-4), 16, 16,
360*(1-ang), 360*ang, ArcType.ROUND);
                        context.strokeArc((x-4), (y-4), 16, 16,
360*(1-ang), 360*ang, (ang == 0 || ang == 1) ? ArcType.OPEN :
ArcType.ROUND);

                        context.setStroke(Color.WHITE);
                        context.setFill(Color.RED);
                        context.setLineWidth(1);
                        ang =
node.getSatPressure()[step]/node.getTotal();
                        context.fillArc(x, y, 8, 8, 0, 360*(1-ang),
ArcType.ROUND);
```

```
                                context.strokeArc(x, y, 8, 8, 0, 360*(1-
ang), (ang == 0 || ang == 1) ? ArcType.OPEN : ArcType.ROUND);
                                context.setStroke(Color.WHITE);
                                context.setFill(Color.GREEN);
                                context.fillArc(x, y, 8, 8, 360*(1-ang),
360*ang, ArcType.ROUND);
                                context.strokeArc(x, y, 8, 8, 360*(1-ang),
360*ang, (ang == 0 || ang == 1) ? ArcType.OPEN : ArcType.ROUND);


arc.addEventHandler(MouseEvent.MOUSE_CLICKED, new
EventHandler<MouseEvent>() {
                                @Override public void handle(MouseEvent
e) {

                                    double minX = Double.MAX_VALUE;
                                    double minY = Double.MAX_VALUE;
                                    double maxY = -1;

                                    graph.getData().clear();
                                    for (double[] array :
node.getPre()) {
                                        XYChart.Series series = new
XYChart.Series();
                                        int step = 96;
                                        Ids = node.getPreIds();
                                        series.setName("Node " +
Integer.toString(node.getSimpleID()));
                                        for (double d : array) {
                                            series.getData().add(new
XYChart.Data(step, d));
                                            step++;
                                        }
                                        graph.getData().add(series);
                                    }
                                    for (Arc a: origArcs) {
                                        if (Integer.parseInt(a.getId())
== Integer.parseInt(arc.getId())) {
                                            if (!selectMode) {

conOrig.strokeArc(a.getCenterX() - conOrig.getCanvas().getLayoutX() -
2, a.getCenterY() - conOrig.getCanvas().getLayoutY() - 2, 4, 4, 0, 360,
ArcType.OPEN);
                                            }
                                            if (minX > a.getCenterX() -
conOrig.getCanvas().getLayoutX()) {
                                                minX = a.getCenterX() -
conOrig.getCanvas().getLayoutX();
                                            }
                                            if (minY > a.getCenterY() -
conOrig.getCanvas().getLayoutY()) {
                                                minY = a.getCenterY() -
conOrig.getCanvas().getLayoutY();
                                            }
                                            if (maxY < a.getCenterY() -
conOrig.getCanvas().getLayoutY()) {
                                                maxY = a.getCenterY() -
conOrig.getCanvas().getLayoutY();
                                            }
                                        }
                                    }
                                    for (Polyline p: origLinks) {
                                        if (Integer.parseInt(p.getId())
== Integer.parseInt(arc.getId())) {
                                            if (minX >
p.getPoints().get(0) - conOrigLinks.getCanvas().getLayoutX()) {
```

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```
                                            minX =
p.getPoints().get(0) - conOrigLinks.getCanvas().getLayoutX();
                                        }
                                        if (minY >
p.getPoints().get(1) - conOrigLinks.getCanvas().getLayoutY()) {
                                            minY =
p.getPoints().get(1) - conOrigLinks.getCanvas().getLayoutY();
                                        }
                                        if (maxY <
p.getPoints().get(1) - conOrigLinks.getCanvas().getLayoutY()) {
                                            maxY =
p.getPoints().get(1) - conOrigLinks.getCanvas().getLayoutY();
                                        }
                                        if (minX >
p.getPoints().get(2) - conOrigLinks.getCanvas().getLayoutX()) {
                                            minX =
p.getPoints().get(2) - conOrigLinks.getCanvas().getLayoutX();
                                        }
                                        if (minY >
p.getPoints().get(3) - conOrigLinks.getCanvas().getLayoutY()) {
                                            minY =
p.getPoints().get(3) - conOrigLinks.getCanvas().getLayoutY();
                                        }
                                        if (maxY <
p.getPoints().get(3) - conOrigLinks.getCanvas().getLayoutY()) {
                                            maxY =
p.getPoints().get(3) - conOrigLinks.getCanvas().getLayoutY();
                                        }
                                    }
                                }
                                simpleID =
Integer.parseInt(arc.getId());

                                int[] range = {0, 0};

                                conOrig.translate(-
conOrig.getTransform().getTx(), -conOrig.getTransform().getTy());
                                conOrigLinks.translate(-
conOrigLinks.getTransform().getTx(), -
conOrigLinks.getTransform().getTy());
                                conOrigLinks.clearRect(0, 0, 208,
380);
                                conOrig.clearRect(0, 0, 208, 380);
                                if (selectMode) {
                                    double zoomRange = (maxY - minY
+ 4);
                                    if (zoomRange < 0.25*(208-
0/380.0)) {
                                        scale = 8.0;
                                    } else {
                                        scale = 2.0;
                                    }

                                    conOrigLinks.translate(-
(scale*minX - scale*6), -(scale*minY - scale*6));
                                    conOrigLinks.scale(scale,
scale);
                                    conOrig.translate(-(scale*minX
- scale*6), -(scale*minY - scale*6));
                                    conOrig.scale(scale, scale);
                                }
                                drawLinks(conOrigLinks,
readers[scenario], 1, 208, 380, range);
                                drawNodes(conOrig,
readers[scenario], "orig", 208, 380, range);
                                if (selectMode) {
```

```
                                                    conOrigLinks.scale(1.0/scale,
1.0/scale);
                                                    conOrig.scale(1.0/scale,
1.0/scale);
                                        }
                                    }
                                });
                                this.arcs.add(arc);
                            }
                            context.setFill(Color.BLACK);
                            context.fillText((step+96) + "-" + (step+97),
offX + 120, offY + 45);
                            offX += offsetX;
                            step += 1;
                        }
                        offY += offsetY;
                    }
                    break;
                case "age" :
                    context.clearRect(0, 0, context.getCanvas().getWidth(),
context.getCanvas().getHeight());
                    this.arcs.clear();
                    while (offY < 730) {
                        offX = 0;
                        while (offX < 910 && step <= range[1]) {
                            for (final Node node : reader.getNodes()) {
                                final Arc arc = new Arc();

arc.setId(Integer.toString(node.getSimpleID()));
                                arc.setFill(Color.BLACK);
                                context.setStroke(Color.BLACK);
                                context.setFill(Color.GOLD);
                                context.setLineWidth(0.5);
                                x = scaleCoordinates(offsetX, node.getX(),
reader.getMinX(), reader.getMaxX(), 0) - 4 + offX;
                                y = scaleCoordinates(offsetY, node.getY(),
reader.getMinY(), reader.getMaxY(), 1) - 4 + offY;

                                arc.setCenterX(x +
context.getCanvas().getLayoutX() + 4);
                                arc.setCenterY(y +
context.getCanvas().getLayoutY() + 4);
                                arc.setRadiusX(8);
                                arc.setRadiusY(8);
                                arc.setStartAngle(0);
                                arc.setLength(360);
                                arc.setType(ArcType.ROUND);
                                arc.setOpacity(0);

                                ang =
node.getSatAge()[step+1]/node.getTotal();
                                context.fillArc((x-4), (y-4), 16, 16, 0,
360*(1-ang), ArcType.ROUND);
                                context.strokeArc((x-4), (y-4), 16, 16, 0,
360*(1-ang), (ang == 0 || ang == 1) ? ArcType.OPEN : ArcType.ROUND);
                                context.setStroke(Color.WHITE);
                                context.setFill(Color.NAVY);
                                context.fillArc((x-4), (y-4), 16, 16,
360*(1-ang), 360*ang, ArcType.ROUND);
                                context.strokeArc((x-4), (y-4), 16, 16,
360*(1-ang), 360*ang, (ang == 0 || ang == 1) ? ArcType.OPEN :
ArcType.ROUND);

                                context.setStroke(Color.BLACK);
                                context.setFill(Color.GOLD);
                                context.setLineWidth(1);
```

```
                                                ang =
node.getSatAge()[step]/node.getTotal();
                                        context.fillArc(x, y, 8, 8, 0, 360*(1-ang),
ArcType.ROUND);
                                        context.strokeArc(x, y, 8, 8, 0, 360*(1-
ang), (ang == 0 || ang == 1) ? ArcType.OPEN : ArcType.ROUND);
                                        context.setStroke(Color.WHITE);
                                        context.setFill(Color.NAVY);
                                        context.fillArc(x, y, 8, 8, 360*(1-ang),
360*ang, ArcType.ROUND);
                                        context.strokeArc(x, y, 8, 8, 360*(1-ang),
360*ang, (ang == 0 || ang == 1) ? ArcType.OPEN : ArcType.ROUND);


arc.addEventHandler(MouseEvent.MOUSE_CLICKED, new
EventHandler<MouseEvent>() {
                                        @Override public void handle(MouseEvent
e) {

                                                double minX = Double.MAX_VALUE;
                                                double minY = Double.MAX_VALUE;
                                                double maxY = -1;

                                                graph.getData().clear();
                                                for (double[] array :
node.getQua()) {
                                                        XYChart.Series series = new
XYChart.Series();
                                                        int step = 96;
                                                        Ids = node.getQuaIds();
                                                        series.setName("Node " +
Integer.toString(node.getSimpleID()));
                                                        for (double d : array) {
                                                                series.getData().add(new
XYChart.Data(step, d));
                                                                step++;
                                                        }
                                                        graph.getData().add(series);
                                                }
                                                for (Arc a: origArcs) {
                                                        if (Integer.parseInt(a.getId())
== Integer.parseInt(arc.getId())) {
                                                                if (minX > a.getCenterX() -
conOrig.getCanvas().getLayoutX()) {
                                                                        minX = a.getCenterX() -
conOrig.getCanvas().getLayoutX();
                                                                }
                                                                if (minY > a.getCenterY() -
conOrig.getCanvas().getLayoutY()) {
                                                                        minY = a.getCenterY() -
conOrig.getCanvas().getLayoutY();
                                                                }
                                                                if (maxY < a.getCenterY() -
conOrig.getCanvas().getLayoutY()) {
                                                                        maxY = a.getCenterY() -
conOrig.getCanvas().getLayoutY();
                                                                }
                                                        }
                                                }
                                                for (Polyline p: origLinks) {
                                                        if (Integer.parseInt(p.getId())
== Integer.parseInt(arc.getId())) {
                                                                if (minX >
p.getPoints().get(0) - conOrigLinks.getCanvas().getLayoutX()) {
                                                                        minX =
p.getPoints().get(0) - conOrigLinks.getCanvas().getLayoutX();
```

```
                                                    }
                                                    if (minY >
p.getPoints().get(1) - conOrigLinks.getCanvas().getLayoutY()) {
                                                        minY =
p.getPoints().get(1) - conOrigLinks.getCanvas().getLayoutY();
                                                    }
                                                    if (maxY <
p.getPoints().get(1) - conOrigLinks.getCanvas().getLayoutY()) {
                                                        maxY =
p.getPoints().get(1) - conOrigLinks.getCanvas().getLayoutY();
                                                    }
                                                    if (minX >
p.getPoints().get(2) - conOrigLinks.getCanvas().getLayoutX()) {
                                                        minX =
p.getPoints().get(2) - conOrigLinks.getCanvas().getLayoutX();
                                                    }
                                                    if (maxY <
p.getPoints().get(3) - conOrigLinks.getCanvas().getLayoutY()) {
                                                        maxY =
p.getPoints().get(3) - conOrigLinks.getCanvas().getLayoutY();
                                                    }
                                                }
                                            }

                                            simpleID =
Integer.parseInt(arc.getId());

                                            int[] range = {0, 0};

                                            conOrig.translate(-
conOrig.getTransform().getTx(), -conOrig.getTransform().getTy());
                                            conOrigLinks.translate(-
conOrigLinks.getTransform().getTx(), -
conOrigLinks.getTransform().getTy());
                                            conOrigLinks.clearRect(0, 0, 208,
380);
                                            conOrig.clearRect(0, 0, 208, 380);
                                            if (selectMode) {
                                                double zoomRange = (maxY - minY
+ 4);
                                                if (zoomRange < 0.25*(208-
0/380.0)) {
                                                    scale = 8.0;
                                                } else {
                                                    scale = 2.0;
                                                }
                                                conOrigLinks.translate(-
(scale*minX - scale*6), -(scale*minY - scale*6));
                                                conOrigLinks.scale(scale,
scale);
                                                conOrig.translate(-(scale*minX
- scale*6), -(scale*minY - scale*6));
                                                conOrig.scale(scale, scale);
                                            }
                                            drawLinks(conOrigLinks,
readers[scenario], 1, 208, 380, range);
                                            drawNodes(conOrig,
readers[scenario], "orig", 208, 380, range);
                                            if (selectMode) {
                                                conOrigLinks.scale(1.0/scale,
1.0/scale);
                                                conOrig.scale(1.0/scale,
1.0/scale);
                                            }
                                        }
```

```java
                                                    });

                                            this.arcs.add(arc);
                                    }
                                    for (final Node node : reader.getDualNodes()) {
                                            final Arc arc = new Arc();

arc.setId(Integer.toString(node.getSimpleID()));
                                            arc.setFill(Color.BLACK);
                                            context.setStroke(Color.WHITE);
                                            context.setFill(Color.RED);
                                            context.setLineWidth(0.5);
                                            x = scaleCoordinates(offsetX, node.getX(),
reader.getMinX(), reader.getMaxX(), 0) - 4 + offX - 100;
                                            y = scaleCoordinates(offsetY, node.getY(),
reader.getMinY(), reader.getMaxY(), 1) - 4 + offY;

                                            arc.setCenterX(x +
context.getCanvas().getLayoutX() + 4);
                                            arc.setCenterY(y +
context.getCanvas().getLayoutY() + 4);
                                            arc.setRadiusX(8);
                                            arc.setRadiusY(8);
                                            arc.setStartAngle(0);
                                            arc.setLength(360);
                                            arc.setType(ArcType.ROUND);
                                            arc.setOpacity(0);

                                            ang =
node.getSatAge()[step+1]/node.getTotal();

                                            context.fillArc((x-4), (y-4), 16, 16, 0,
360*(1-ang), ArcType.ROUND);
                                            context.strokeArc((x-4), (y-4), 16, 16, 0,
360*(1-ang), (ang == 0 || ang == 1) ? ArcType.OPEN : ArcType.ROUND);
                                            context.setStroke(Color.WHITE);
                                            context.setFill(Color.GREEN);
                                            context.fillArc((x-4), (y-4), 16, 16,
360*(1-ang), 360*ang, ArcType.ROUND);
                                            context.strokeArc((x-4), (y-4), 16, 16,
360*(1-ang), 360*ang, (ang == 0 || ang == 1) ? ArcType.OPEN :
ArcType.ROUND);

                                            context.setStroke(Color.WHITE);
                                            context.setFill(Color.RED);
                                            context.setLineWidth(1);
                                            ang =
node.getSatAge()[step]/node.getTotal();
                                            context.fillArc(x, y, 8, 8, 0, 360*(1-ang),
ArcType.ROUND);
                                            context.strokeArc(x, y, 8, 8, 0, 360*(1-
ang), (ang == 0 || ang == 1) ? ArcType.OPEN : ArcType.ROUND);
                                            context.setStroke(Color.WHITE);
                                            context.setFill(Color.GREEN);
                                            context.fillArc(x, y, 8, 8, 360*(1-ang),
360*ang, ArcType.ROUND);
                                            context.strokeArc(x, y, 8, 8, 360*(1-ang),
360*ang, (ang == 0 || ang == 1) ? ArcType.OPEN : ArcType.ROUND);


arc.addEventHandler(MouseEvent.MOUSE_CLICKED, new
EventHandler<MouseEvent>() {
                                                    @Override public void handle(MouseEvent
e) {

                                                            double minX = Double.MAX_VALUE;
```

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```java
                                double minY = Double.MAX_VALUE;
                                double maxY = -1;

                                graph.getData().clear();
                                for (double[] array :
node.getQua()) {
                                    XYChart.Series series = new
XYChart.Series();
                                    int step = 96;
                                    Ids = node.getQuaIds();
                                    series.setName("Node " +
Integer.toString(node.getSimpleID()));
                                    for (double d : array) {
                                        series.getData().add(new
XYChart.Data(step, d));
                                        step++;
                                    }
                                    graph.getData().add(series);
                                }
                                for (Arc a: origArcs) {
                                    if (Integer.parseInt(a.getId())
== Integer.parseInt(arc.getId())) {
                                        if (minX > a.getCenterX() -
conOrig.getCanvas().getLayoutX()) {
                                            minX = a.getCenterX() -
conOrig.getCanvas().getLayoutX();
                                        }
                                        if (minY > a.getCenterY() -
conOrig.getCanvas().getLayoutY()) {
                                            minY = a.getCenterY() -
conOrig.getCanvas().getLayoutY();
                                        }
                                        if (maxY < a.getCenterY() -
conOrig.getCanvas().getLayoutY()) {
                                            maxY = a.getCenterY() -
conOrig.getCanvas().getLayoutY();
                                        }
                                    }
                                }
                                for (Polyline p: origLinks) {
                                    if (Integer.parseInt(p.getId())
== Integer.parseInt(arc.getId())) {
                                        if (minX >
p.getPoints().get(0) - conOrigLinks.getCanvas().getLayoutX()) {
                                            minX =
p.getPoints().get(0) - conOrigLinks.getCanvas().getLayoutX();
                                        }
                                        if (minY >
p.getPoints().get(1) - conOrigLinks.getCanvas().getLayoutY()) {
                                            minY =
p.getPoints().get(1) - conOrigLinks.getCanvas().getLayoutY();
                                        }
                                        if (maxY <
p.getPoints().get(1) - conOrigLinks.getCanvas().getLayoutY()) {
                                            maxY =
p.getPoints().get(1) - conOrigLinks.getCanvas().getLayoutY();
                                        }
                                        if (minX >
p.getPoints().get(2) - conOrigLinks.getCanvas().getLayoutX()) {
                                            minX =
p.getPoints().get(2) - conOrigLinks.getCanvas().getLayoutX();
                                        }
                                        if (minY >
p.getPoints().get(3) - conOrigLinks.getCanvas().getLayoutY()) {
                                            minY =
p.getPoints().get(3) - conOrigLinks.getCanvas().getLayoutY();
```

```java
                                                    }
                                                    if (maxY <
p.getPoints().get(3) - conOrigLinks.getCanvas().getLayoutY()) {
                                                        maxY =
p.getPoints().get(3) - conOrigLinks.getCanvas().getLayoutY();
                                                    }
                                                }
                                            }

                                            simpleID =
Integer.parseInt(arc.getId());

                                            int[] range = {0, 0};

                                            conOrig.translate(-
conOrig.getTransform().getTx(), -conOrig.getTransform().getTy());
                                            conOrigLinks.translate(-
conOrigLinks.getTransform().getTx(), -
conOrigLinks.getTransform().getTy());
                                            conOrigLinks.clearRect(0, 0, 208,
380);
                                            conOrig.clearRect(0, 0, 208, 380);
                                            if (selectMode) {
                                                double zoomRange = (maxY - minY
+ 4);

                                                if (zoomRange < 0.25*(208-
0/380.0)) {

                                                    scale = 8.0;
                                                } else {
                                                    scale = 2.0;
                                                }

                                                conOrigLinks.translate(-
(scale*minX - scale*6), -(scale*minY - scale*6));
                                                conOrigLinks.scale(scale,
scale);
                                                conOrig.translate(-(scale*minX
- scale*6), -(scale*minY - scale*6));
                                                conOrig.scale(scale, scale);
                                            }
                                            drawLinks(conOrigLinks,
readers[scenario], 1, 208, 380, range);
                                            drawNodes(conOrig,
readers[scenario], "orig", 208, 380, range);
                                            if (selectMode) {
                                                conOrigLinks.scale(1.0/scale,
1.0/scale);
                                                conOrig.scale(1.0/scale,
1.0/scale);
                                            }
                                        }
                                    });

                                    this.arcs.add(arc);
                                }
                                context.setFill(Color.BLACK);
                                context.fillText((step+96) + "-" + (step+97),
offX + 120, offY + 45);
                                offX += offsetX;
                                step += 1;
                            }
                            offY += offsetY;
                        }
                    break;
                case "orig" :
```

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```
                context.clearRect(0, 0, context.getCanvas().getWidth(),
context.getCanvas().getHeight());
                origArcs.clear();
                Color[] colors = {Color.rgb(230, 126, 157).darker(),
Color.rgb(79, 214, 86).darker(), Color.rgb(91, 77, 214).darker(),
Color.rgb(68, 154, 173).darker(), Color.rgb(222, 211, 138).darker()};
                for (Node node : reader.getNodesOrig()) {
                    final Arc arc = new Arc();
                    arc.setId(Integer.toString(node.getSimpleID()));

arc.setFill(colors[Integer.parseInt(node.getZoneId().substring(5))-1]);
                    if (Ids.contains(node.getId()) && simpleID != -1) {
                        int pos = Ids.indexOf(node.getId());
                        if (pos > 7) {
                            conOrig.setFill(lineChartColors[0]);
                        } else {
                            conOrig.setFill(lineChartColors[pos]);
                        }
                        System.out.println(conOrig.getFill() + " " +
pos);
                    } else {

conOrig.setFill(colors[Integer.parseInt(node.getZoneId().substring(5))-
1]);
                    }
                    x = scaleCoordinates(offsetX, node.getX(),
reader.getMinX(), reader.getMaxX(), 0);
                    y = scaleCoordinates(offsetY, node.getY(),
reader.getMinY() - 1000, reader.getMaxY()+10000, 1);

                    arc.setCenterX(x +
context.getCanvas().getLayoutX());
                    arc.setCenterY(y +
context.getCanvas().getLayoutY());
                    arc.setRadiusX(2);
                    arc.setRadiusY(2);
                    arc.setStartAngle(0);
                    arc.setLength(360);
                    arc.setType(ArcType.ROUND);
                    arc.setOpacity(0);

                    double radius;

                    if (scale > 2) {
                        radius = 1.5;
                        context.setLineWidth(0.2);
                    } else {
                        radius = 4.0;
                        context.setLineWidth(1);
                    }

                    this.origArcs.add(arc);
                    context.fillArc(x - 0.5*radius, y - 0.5*radius,
radius, radius, 0, 360, ArcType.ROUND);
                    if (node.getSimpleID() == simpleID) {
                        context.setStroke(Color.YELLOW);
                    } else {
                        context.setStroke(Color.BLACK);
                    }
                    context.strokeArc(x - 0.5*radius, y - 0.5*radius,
radius, radius, 0, 360, ArcType.OPEN);
                }
                for (Node node : reader.getDualOrig()) {
                    final Arc arc = new Arc();
                    arc.setId(Integer.toString(node.getSimpleID()));
                    /*
```

```java
                        * deepened color for dual extend
                        */
                        arc.setFill(Color.ORANGE);
                        context.setFill(Color.ORANGE);

                        if (Ids.contains(node.getId())) {
                            int pos = Ids.indexOf(node.getId());
                            if (pos > 7) {
                                conOrig.setFill(lineChartColors[0]);
                            } else {
                                conOrig.setFill(lineChartColors[pos]);
                            }
                            System.out.println(conOrig.getFill() + " " +
pos);
                        } else {
                            conOrig.setFill(Color.ORANGE);
                        }

                        x = scaleCoordinates(208, node.getX(),
reader.getMinX(), reader.getMaxX(), 0) - 40;
                        y = scaleCoordinates(380, node.getY(),
reader.getMinY() - 1000, reader.getMaxY()+10000, 1);

                        arc.setCenterX(x +
context.getCanvas().getLayoutX());
                        arc.setCenterY(y +
conOrig.getCanvas().getLayoutY());
                        arc.setRadiusX(2);
                        arc.setRadiusY(2);
                        arc.setStartAngle(0);
                        arc.setLength(360);
                        arc.setType(ArcType.ROUND);
                        arc.setOpacity(0);

                        double radius;

                        if (scale > 2) {
                            radius = 1.5;
                            context.setLineWidth(0.2);
                        } else {
                            radius = 4.0;
                            context.setLineWidth(1);
                        }

                        this.origArcs.add(arc);
                        context.fillArc(x - 0.5*radius, y - 0.5*radius,
radius, radius, 0, 360, ArcType.ROUND);
                        if (node.getSimpleID() == simpleID) {
                            context.setStroke(Color.YELLOW);
                        } else {
                            context.setStroke(Color.BLACK);
                        }
                        context.strokeArc(x - 0.5*radius, y - 0.5*radius,
radius, radius, 0, 360, ArcType.OPEN);
                    }
                    break;
            }

    }

    /**
     *
     * @param context GraphicsContext to draw on.
     * @param reader ShapefileReader with scenario data to draw.
     * @param offsetX For calculating the links' necessary offset in
direction of the x-axis in the multiple map view.
```

```
     * @param offsetY For calculating the links' necessary offset in
direction of the y.axis in the multiple map view.
     * @param range Only needed for multiple map view. Indicates number
of maps on canvas.
     */
    public void drawZones(GraphicsContext context, ShapefileReader
reader, double offsetX, double offsetY, int[] range) {

        double[] x;
        double[] x2;
        double[] y;
        double offX;
        double offY = 0;
        int step = 0;
        int max = range[1] - range[0];
        Color[] colors = {Color.rgb(230, 126, 157, 0.3), Color.rgb(79,
214, 86, 0.3), Color.rgb(91, 77, 214, 0.3), Color.rgb(68, 154, 173,
0.3), Color.rgb(222, 211, 138, 0.3)};

        context.clearRect(0, 0, context.getCanvas().getWidth(),
context.getCanvas().getHeight());
        while (offY < 730) {
            offX = 0;
            while (offX < 910 && step <= max) {
                for (Zone zone : reader.getZones()) {
                    context.setFill(colors[zone.getId()-1]);
                    x = new double[zone.getX().size()];
                    y = new double[zone.getY().size()];
                    for (int i = 0; i < zone.getX().size(); i++) {
                        x[i] = scaleCoordinates(offsetX,
zone.getX().get(i), reader.getMinX(), reader.getMaxX(), 0) + offX;
                        y[i] = scaleCoordinates(offsetY,
zone.getY().get(i), reader.getMinY(), reader.getMaxY(), 1) + offY;
                    }
                    context.fillPolygon(x, y, x.length);
                }
                for (Zone zone : reader.getDualZone()) {
                    context.setStroke(Color.BLACK);
                    x = new double[zone.getX().size()];
                    x2 = new double[zone.getX().size()];
                    y = new double[zone.getY().size()];
                    for (int i = 0; i < zone.getX().size(); i++) {
                        x[i] = scaleCoordinates(offsetX,
zone.getX().get(i), reader.getMinX(), reader.getMaxX(), 0) + offX -
100;
                        x2[i] = scaleCoordinates(offsetX,
zone.getX().get(i), reader.getMinX(), reader.getMaxX(), 0) + offX;
                        y[i] = scaleCoordinates(offsetY,
zone.getY().get(i), reader.getMinY(), reader.getMaxY(), 1) + offY;
                    }
                    context.strokePolygon(x, y, x.length);
                    context.setStroke(Color.CRIMSON);
                    context.strokePolygon(x2, y, x.length);
                }
                offX += offsetX;
                step++;
            }
            offY += offsetY;
        }
    }

    /**
     *
     * Setup of all controls and interactions.
     * Clickable nodes are deleted when changing scenario or timestep
in case less or more maps are needed.
```

```
    * @throws java.lang.Exception Exceptions when reading shapefiles.
    */
   @Override
   public void start(Stage primaryStage) throws Exception {

       window.setPrefSize(1200, 900);
       window.setMinSize(900, 600);

       ScrollPane sp = new ScrollPane();
       sp.setPrefSize(1200, 900);

       ChoiceBox chooseScene = new ChoiceBox();
       chooseScene.setLayoutX(993);
       chooseScene.setLayoutY(39);
       chooseScene.setPrefWidth(150);
       AnchorPane.setTopAnchor(chooseScene, 39.0);
       AnchorPane.setRightAnchor(chooseScene, 57.0);

chooseScene.setItems(FXCollections.observableArrayList("Baseline", "New
pump without fire flow", "New pump with fire flow",
               "Dual WDS for non-potable water demand", "Dual WDS for
outdoor irrigation", "Hybrid system for non-potable water demand",
"Hybrid system for outdoor irrigation"));
       chooseScene.setValue("Baseline");

       CheckBox zones = new CheckBox("Show zones");
       zones.setLayoutX(993);
       zones.setLayoutY(76);
       zones.setSelected(true);
       AnchorPane.setTopAnchor(zones, 76.0);
       AnchorPane.setRightAnchor(zones, 123.0);

       Separator sep1 = new Separator();
       sep1.setLayoutX(972);
       sep1.setLayoutY(97);
       sep1.setPrefWidth(200);
       AnchorPane.setTopAnchor(sep1, 97.0);
       AnchorPane.setRightAnchor(sep1, 28.0);

       final ToggleGroup radios = new ToggleGroup();
       RadioButton pressure = new RadioButton("Nodal pressure");
       pressure.setUserData("Nodal pressure");
       pressure.setToggleGroup(radios);
       pressure.setSelected(true);
       pressure.setLayoutX(993);
       pressure.setLayoutY(100);
       AnchorPane.setTopAnchor(pressure, 100.0);
       AnchorPane.setRightAnchor(pressure, 105.0);
       RadioButton age = new RadioButton("Water age");
       age.setUserData("Water age");
       age.setToggleGroup(radios);
       age.setLayoutX(993);
       age.setLayoutY(120);
       AnchorPane.setTopAnchor(age, 120.0);
       AnchorPane.setRightAnchor(age, 131.0);

       Separator sep2 = new Separator();
       sep2.setLayoutX(972);
       sep2.setLayoutY(141);
       sep2.setPrefWidth(200);
       AnchorPane.setTopAnchor(sep2, 141.0);
       AnchorPane.setRightAnchor(sep2, 28.0);

       Label label2 = new Label("starting timestep");
       label2.setLayoutX(1015);
       label2.setLayoutY(140);
```

```java
        final Slider startTime = new Slider();
        startTime.setLayoutX(993);
        startTime.setLayoutY(156);
        startTime.setPrefWidth(150);
        startTime.setMin(96);
        startTime.setMax(113);
        startTime.setValue(96);
        startTime.setMajorTickUnit(1);
        startTime.setShowTickMarks(true);
        startTime.setShowTickLabels(true);
        startTime.setSnapToTicks(true);

        final ToggleGroup select = new ToggleGroup();
        RadioButton sel = new RadioButton("Zoom");
        sel.setUserData("Zoom");
        sel.setToggleGroup(select);
        sel.setSelected(true);
        sel.setLayoutX(993);
        sel.setLayoutY(191);
        RadioButton unsel = new RadioButton("Overview");
        unsel.setUserData("Overview");
        unsel.setToggleGroup(select);
        unsel.setLayoutX(1063);
        unsel.setLayoutY(191);

        final Canvas canvasZones = new Canvas(914, 736);
        canvasZones.setLayoutX(24);
        canvasZones.setLayoutY(24);
        AnchorPane.setTopAnchor(canvasZones, 24.0);
        AnchorPane.setLeftAnchor(canvasZones, 24.0);
        AnchorPane.setRightAnchor(canvasZones, 252.0);
        final Canvas canvasLinks = new Canvas(914, 736);
        canvasLinks.setLayoutX(24);
        canvasLinks.setLayoutY(24);
        AnchorPane.setTopAnchor(canvasLinks, 24.0);
        AnchorPane.setLeftAnchor(canvasLinks, 24.0);
        AnchorPane.setRightAnchor(canvasLinks, 252.0);
        final Canvas canvas = new Canvas(914, 736);
        canvas.setLayoutX(24);
        canvas.setLayoutY(24);
        AnchorPane.setTopAnchor(canvas, 24.0);
        AnchorPane.setLeftAnchor(canvas, 24.0);
        AnchorPane.setRightAnchor(canvas, 252.0);
        AnchorPane.setBottomAnchor(canvas, 24.0);
        canOrigLinks = new Canvas(208, 380);
        canOrigLinks.setLayoutX(968);
        canOrigLinks.setLayoutY(285);
        AnchorPane.setLeftAnchor(canOrigLinks, 968.0);
        AnchorPane.setRightAnchor(canOrigLinks, 24.0);
        canOrig = new Canvas(208, 380);
        canOrig.setLayoutX(968);
        canOrig.setLayoutY(285);
        AnchorPane.setLeftAnchor(canOrig, 968.0);
        AnchorPane.setRightAnchor(canOrig, 24.0);

        final GraphicsContext contextZones =
canvasZones.getGraphicsContext2D();
        final GraphicsContext contextLinks =
canvasLinks.getGraphicsContext2D();
        final GraphicsContext context = canvas.getGraphicsContext2D();
        conOrigLinks = canOrigLinks.getGraphicsContext2D();
        conOrig = canOrig.getGraphicsContext2D();

        conOrigLinks.setStroke(Color.WHITE);
        conOrigLinks.setFill(Color.WHITE);
```

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```java
        conOrigLinks.setLineWidth(1);

        zones.selectedProperty().addListener(new
ChangeListener<Boolean>() {
                @Override public void changed(ObservableValue<? extends
Boolean> ov, Boolean old_val, Boolean new_val)  {
                    if (new_val == true) {
                        canvasZones.setVisible(true);
                    } else {
                        canvasZones.setVisible(false);
                    }
                }
        });

        Button clear = new Button("Clear selection");
        clear.setLayoutX(993);
        clear.setLayoutY(221);
        clear.setPrefWidth(150);

        /*Button load = new Button("Load File");
        load.setLayoutX(993);
        load.setLayoutY(638);
        load.setPrefWidth(150);
        AnchorPane.setRightAnchor(load, 58.0);
        AnchorPane.setBottomAnchor(load, 137.0);*/

        NumberAxis xAxis = new NumberAxis("timestep", 96, 119, 1);
        NumberAxis yAxis = new NumberAxis("pressure", 0, 100, 10);
        graph = new LineChart(xAxis, yAxis);
        graph.setLayoutX(24);
        graph.setLayoutY(760);
        graph.setPrefSize(450, 120);

        Image leg = new Image("file:legend_.jpg", 400, 120, true,
true);
        ImageView legend = new ImageView();
        legend.setLayoutX(490);
        legend.setLayoutY(760);
        legend.setImage(leg);

        final TableView table = new TableView();
        table.setLayoutX(920);
        table.setLayoutY(680);
        table.setPrefSize(250, 100);
        table.setEditable(false);
        TableColumn zone = new TableColumn("Zones");
        TableColumn SIpre = new TableColumn("SIpressure");
        TableColumn SIage = new TableColumn("SIwaterage");
        zone.setCellValueFactory(new PropertyValueFactory<ZoneValues,
String>("ID"));
        SIpre.setCellValueFactory(new PropertyValueFactory<ZoneValues,
String>("press"));
        SIage.setCellValueFactory(new PropertyValueFactory<ZoneValues,
String>("age"));
        zone.setMinWidth(60);
        SIpre.setMinWidth(60);
        SIage.setMinWidth(60);

        final TableView table2 = new TableView();
        table2.setLayoutX(920);
        table2.setLayoutY(790);
        table2.setPrefSize(250, 100);
        table2.setEditable(false);
        TableColumn name = new TableColumn("Property");
        TableColumn val = new TableColumn("Value");
```

```java
        name.setCellValueFactory(new PropertyValueFactory<MiscValues,
String>("name"));
        val.setCellValueFactory(new PropertyValueFactory<MiscValues,
String>("val"));
        name.setMinWidth(180);
        val.setMinWidth(50);

        final ObservableList<ZoneValues> data =
FXCollections.observableArrayList();
        final ObservableList<MiscValues> data2 =
FXCollections.observableArrayList();

        window.getChildren().add(chooseScene);
        window.getChildren().add(zones);
        window.getChildren().add(sep1);
        window.getChildren().add(pressure);
        window.getChildren().add(age);
        window.getChildren().add(sep2);
        window.getChildren().add(label2);
        window.getChildren().add(startTime);
        window.getChildren().add(sel);
        window.getChildren().add(clear);
        window.getChildren().add(unsel);
        window.getChildren().add(canvasZones);
        window.getChildren().add(canvasLinks);
        window.getChildren().add(canvas);
        window.getChildren().add(canOrigLinks);
        window.getChildren().add(canOrig);
        window.getChildren().add(legend);
        window.getChildren().add(graph);
        window.getChildren().add(table);
        window.getChildren().add(table2);
        sp.setContent(window);

        for (int i = 0; i < 7; i++) {
            readers[i] = new ShapefileReader();
        }
        try {
            readers[0].loadFiles("BASELINESCENARIODATA", 0);
        } catch (Exception e) {
            System.out.println("Error occured while reading shapefile:
" + e.toString());
        }
        try {

readers[1].loadFiles("BASELINESCENARIODATA/SCENARIOS/NEWPUMP/NOFIREFLOW
", 1);
        } catch (Exception e) {
            System.out.println("Error occured while reading shapefile:
" + e.toString());
        }
        try {

readers[2].loadFiles("BASELINESCENARIODATA/SCENARIOS/NEWPUMP/WITHFIREFL
OW", 2);
        } catch (Exception e) {
            System.out.println("Error occured while reading shapefile:
" + e.toString());
        }
        try {
            readers[3].loadFiles("BASELINESCENARIODATA/SCENARIOS", 3);
        } catch (Exception e) {
            System.out.println("Error occured while reading shapefile:
" + e.toString());
        }
        try {
```

```
            readers[4].loadFiles("BASELINESCENARIODATA/SCENARIOS", 4);
        } catch (Exception e) {
            System.out.println("Error occured while reading shapefile:
" + e.toString());
        }
        try {
            readers[5].loadFiles("BASELINESCENARIODATA/SCENARIOS", 5);
        } catch (Exception e) {
            System.out.println("Error occured while reading shapefile:
" + e.toString());
        }
        try {
            readers[6].loadFiles("BASELINESCENARIODATA/SCENARIOS", 6);
        } catch (Exception e) {
            System.out.println("Error occured while reading shapefile:
" + e.toString());
        }


chooseScene.getSelectionModel().selectedIndexProperty().addListener(new
ChangeListener<Number>() {
            @Override public void changed(ObservableValue<? extends
Number> ov, Number old_val, Number new_val) {
                scenario = new_val.intValue();
                int[] toggRange = {(int) startTime.getValue() - 96,
Math.min((int) startTime.getValue() - 96 + 6, 118 - 96)};
                if
(radios.getSelectedToggle().getUserData().toString().equals("Nodal
pressure")) {
                    for (Arc a : arcs) {
                        window.getChildren().remove(a);
                    }
                    drawNodes(context, readers[scenario], "press",
914/3, 736/2, toggRange);
                    for (Arc a : arcs) {
                        window.getChildren().add(a);
                    }
                } else {
                    for (Arc a : arcs) {
                        window.getChildren().remove(a);
                    }
                    drawNodes(context, readers[scenario], "age", 914/3,
736/2, toggRange);
                    for (Arc a : arcs) {
                        window.getChildren().add(a);
                    }
                }
                drawZones(contextZones, readers[scenario], 914/3,
736/2, toggRange);
                drawLinks(contextLinks, readers[scenario], 0, 914/3,
736/2, toggRange);
                drawLinks(conOrigLinks, readers[scenario], 1, 208, 380,
toggRange);
                drawNodes(conOrig, readers[scenario], "orig", 208, 380,
toggRange);
                table.getItems().clear();
                table2.getItems().clear();
                data.clear();
                data2.clear();

                int offset = (scenario > 2) ? 1 : 0;

                for (int i = 0; i < readers[scenario].getZones().size()
+ offset; i++) {
                    data.add(new
ZoneValues(readers[scenario].getTable().get(3*i),
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```
              readers[scenario].getTable().get(3*i+1),
readers[scenario].getTable().get(3*i+2)));
                }

                for (int i = 3*readers[scenario].getZones().size() +
3*offset; i < readers[scenario].getTable().size() - 1; i+=2) {
                    data2.add(new
MiscValues(readers[scenario].getTable().get(i),
readers[scenario].getTable().get(i+1)));
                }
            }
        });

        startTime.valueProperty().addListener(new
ChangeListener<Number>() {
            @Override public void changed(ObservableValue<? extends
Number> ov, Number old_val, Number new_val) {
                int[] toggRange = {new_val.intValue() - 96,
Math.min(new_val.intValue() - 96 + 6, 118 - 96)};
                if
(radios.getSelectedToggle().getUserData().toString().equals("Nodal
pressure")) {
                    for (Arc a : arcs) {
                        window.getChildren().remove(a);
                    }
                    drawNodes(context, readers[scenario], "press",
914/3, 736/2, toggRange);
                    for (Arc a : arcs) {
                        window.getChildren().add(a);
                    }
                } else {
                    for (Arc a : arcs) {
                        window.getChildren().remove(a);
                    }
                    drawNodes(context, readers[scenario], "age", 914/3,
736/2, toggRange);
                    for (Arc a : arcs) {
                        window.getChildren().add(a);
                    }
                }
                drawZones(contextZones, readers[scenario], 914/3,
736/2, toggRange);
                drawLinks(contextLinks, readers[scenario], 0, 914/3,
736/2, toggRange);
            }
        });

        radios.selectedToggleProperty().addListener(new
ChangeListener<Toggle>() {
            @Override public void changed(ObservableValue<? extends
Toggle> ov, Toggle old_toggle, Toggle new_toggle) {
                if (radios.getSelectedToggle() != null) {
                    int[] toggRange = {(int) startTime.getValue() - 96,
Math.min((int) startTime.getValue() - 96 + 6, 118 - 96)};
                    if
(radios.getSelectedToggle().getUserData().toString().equals("Nodal
pressure")) {
                        for (Arc a : arcs) {
                            window.getChildren().remove(a);
                        }
                        drawNodes(context, readers[scenario], "press",
914/3, 736/2, toggRange);
                        for (Arc a : arcs) {
                            window.getChildren().add(a);
                        }
                        graph.getYAxis().setLabel("pressure");
```

```
                    } else {
                        for (Arc a : arcs) {
                            window.getChildren().remove(a);
                        }
                        drawNodes(context, readers[scenario], "age",
914/3, 736/2, toggRange);
                        for (Arc a : arcs) {
                            window.getChildren().add(a);
                        }
                        graph.getYAxis().setLabel("waterage");
                    }
                    drawZones(contextZones, readers[scenario], 914/3,
736/2, toggRange);
                    drawLinks(contextLinks, readers[scenario], 0,
914/3, 736/2, toggRange);
                }
            }
        });

        select.selectedToggleProperty().addListener(new
ChangeListener<Toggle>() {
            @Override public void changed(ObservableValue<? extends
Toggle> ov, Toggle old_toggle, Toggle new_toggle) {
                if (select.getSelectedToggle() != null) {
                    if
(select.getSelectedToggle().getUserData().toString().equals("Overview")
) {
                        selectMode = false;
                        scale = 1.0;
                        int[] range = {0,5};

                        conOrig.translate(-
conOrig.getTransform().getTx(), -conOrig.getTransform().getTy());
                        conOrigLinks.translate(-
conOrigLinks.getTransform().getTx(), -
conOrigLinks.getTransform().getTy());
                        conOrigLinks.clearRect(0, 0, 208, 380);
                        conOrig.clearRect(0, 0, 208, 380);
                        conOrigLinks.scale(scale, scale);
                        conOrig.scale(scale, scale);
                        drawLinks(conOrigLinks, readers[scenario], 1,
208, 380, range);
                        drawNodes(conOrig, readers[scenario], "orig",
208, 380, range);
                    } else {
                        selectMode = true;
                        double minX = Double.MAX_VALUE;
                        double minY = Double.MAX_VALUE;
                        double maxY = -1;
                        for (Arc a: origArcs) {
                            if (Integer.parseInt(a.getId()) ==
simpleID) {
                                if (minX > a.getCenterX() -
conOrig.getCanvas().getLayoutX()) {
                                    minX = a.getCenterX() -
conOrig.getCanvas().getLayoutX();
                                }
                                if (minY > a.getCenterY() -
conOrig.getCanvas().getLayoutY()) {
                                    minY = a.getCenterY() -
conOrig.getCanvas().getLayoutY();
                                }
                                if (maxY < a.getCenterY() -
conOrig.getCanvas().getLayoutY()) {
                                    maxY = a.getCenterY() -
conOrig.getCanvas().getLayoutY();
```

```
                                    }
                                }
                            }
                            for (Polyline p: origLinks) {
                                if (Integer.parseInt(p.getId()) ==
simpleID) {
                                    if (minX > p.getPoints().get(0) -
conOrigLinks.getCanvas().getLayoutX()) {
                                        minX = p.getPoints().get(0) -
conOrigLinks.getCanvas().getLayoutX();
                                    }
                                    if (minY > p.getPoints().get(1) -
conOrigLinks.getCanvas().getLayoutY()) {
                                        minY = p.getPoints().get(1) -
conOrigLinks.getCanvas().getLayoutY();
                                    }
                                    if (maxY < p.getPoints().get(1) -
conOrigLinks.getCanvas().getLayoutY()) {
                                        maxY = p.getPoints().get(1) -
conOrigLinks.getCanvas().getLayoutY();
                                    }
                                    if (minX > p.getPoints().get(2) -
conOrigLinks.getCanvas().getLayoutX()) {
                                        minX = p.getPoints().get(2) -
conOrigLinks.getCanvas().getLayoutX();
                                    }
                                    if (minY > p.getPoints().get(3) -
conOrigLinks.getCanvas().getLayoutY()) {
                                        minY = p.getPoints().get(3) -
conOrigLinks.getCanvas().getLayoutY();
                                    }
                                    if (maxY < p.getPoints().get(3) -
conOrigLinks.getCanvas().getLayoutY()) {
                                        maxY = p.getPoints().get(3) -
conOrigLinks.getCanvas().getLayoutY();
                                    }
                                }
                            }

                            int[] range = {0, 0};

                            conOrig.translate(-
conOrig.getTransform().getTx(), -conOrig.getTransform().getTy());
                            conOrigLinks.translate(-
conOrigLinks.getTransform().getTx(), -
conOrigLinks.getTransform().getTy());
                            conOrigLinks.clearRect(0, 0, 208, 380);
                            conOrig.clearRect(0, 0, 208, 380);

                            double zoomRange = (maxY - minY + 4);
                            if (zoomRange < 0.25*(208-0/380.0)) {
                                scale = 8.0;
                            } else {
                                scale = 2.0;
                            }

                            conOrigLinks.translate(-(scale*minX - scale*6),
-(scale*minY - scale*6));
                            conOrigLinks.scale(scale, scale);
                            conOrig.translate(-(scale*minX - scale*6), -
(scale*minY - scale*6));
                            conOrig.scale(scale, scale);
                            drawLinks(conOrigLinks, readers[scenario], 1,
208, 380, range);
                            drawNodes(conOrig, readers[scenario], "orig",
208, 380, range);
```

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```java
                                conOrigLinks.scale(1.0/scale, 1.0/scale);
                                conOrig.scale(1.0/scale, 1.0/scale);
                    }
                }
            }
        });

        clear.setOnAction(new EventHandler<ActionEvent>() {
            @Override
            public void handle(ActionEvent event) {
                graph.getData().clear();
                System.out.println(Ids);
                simpleID = -1;
                int[] range = {0,0};
                conOrigLinks.clearRect(0, 0, 208, 380);
                conOrig.clearRect(0, 0, 208, 380);
                conOrigLinks.scale(scale, scale);
                conOrig.scale(scale, scale);
                drawLinks(conOrigLinks, readers[scenario], 1, 208, 380,
range);
                drawNodes(conOrig, readers[scenario], "orig", 208, 380,
range);
                conOrigLinks.scale(1.0/scale, 1.0/scale);
                conOrig.scale(1.0/scale, 1.0/scale);
            }
        });

        int[] range = {0,5};

        drawZones(contextZones, readers[scenario], 914/3, 736/2,
range);
        drawLinks(contextLinks, readers[scenario], 0, 914/3, 736/2,
range);
        drawNodes(context, readers[scenario], "press", 914/3, 736/2,
range);
        drawLinks(conOrigLinks, readers[scenario], 1, 208, 380, range);
        drawNodes(conOrig, readers[scenario], "orig", 208, 380, range);

        canOrig.setOnMousePressed(new EventHandler<MouseEvent>() {
            @Override
            public void handle(MouseEvent event) {
                pressedX = event.getX();
                pressedY = event.getY();
            }
        });

        canOrig.setOnMouseDragged(new EventHandler<MouseEvent>() {
            @Override
            public void handle(MouseEvent event) {
                if (selectMode && scale > 1.0) {
                    conOrigLinks.clearRect(0, 0, 208, 380);

conOrigLinks.translate((3.0/scale)*(canOrigLinks.getTranslateX() +
event.getX() - pressedX), (3.0/scale)*(canOrigLinks.getTranslateY() +
event.getY() - pressedY));
                    conOrig.clearRect(0, 0, 208, 380);

conOrig.translate((3.0/scale)*(canOrig.getTranslateX() + event.getX() -
pressedX), (3.0/scale)*(canOrig.getTranslateY() + event.getY() -
pressedY));
                    int[] range = {0,0};
                    conOrig.scale(scale, scale);
                    conOrigLinks.scale(scale, scale);
                    drawLinks(conOrigLinks, readers[scenario], 1, 208,
380, range);
```

```java
                        drawNodes(conOrig, readers[scenario], "orig", 208,
380, range);
                        conOrigLinks.scale(1.0/scale, 1.0/scale);
                        conOrig.scale(1.0/scale, 1.0/scale);

                        event.consume();
                }
            }
        });

        for (Polyline origLink : this.origLinks) {
            window.getChildren().add(origLink);
        }
        for (Arc a : this.origArcs) {
            window.getChildren().add(a);
        }

        for (Arc a : this.arcs) {
            window.getChildren().add(a);
        }

        for (int i = 0; i < readers[scenario].getZones().size(); i++) {
            data.add(new
ZoneValues(readers[scenario].getTable().get(3*i),
readers[scenario].getTable().get(3*i+1),
readers[scenario].getTable().get(3*i+2)));
        }

        for (int i = 3*readers[scenario].getZones().size(); i <
readers[scenario].getTable().size() - 1; i+=2) {
            data2.add(new
MiscValues(readers[scenario].getTable().get(i),
readers[scenario].getTable().get(i+1)));
        }

        table.getColumns().addAll(zone, SIpre, SIage);
        table.setItems(data);

        table2.getColumns().addAll(name, val);
        table2.setItems(data2);

        primaryStage.setTitle("Urban Water System Planning Tool");
        primaryStage.setScene(new Scene(sp));
        primaryStage.show();

    }

    /**
     * The main() method is ignored in correctly deployed JavaFX
application.
     * main() serves only as fallback in case the application can not
be
     * launched through deployment artifacts, e.g., in IDEs with
limited FX
     * support. NetBeans ignores main().
     *
     * @param args the command line arguments
     */
    public static void main(String[] args) {

        launch(args);
    }

    /**
     *
     * Class for tableview items only.
```

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```java
     */
    public static class ZoneValues {

        private final SimpleStringProperty ID;
        private final SimpleStringProperty press;
        private final SimpleStringProperty age;

        private ZoneValues(String ID, String press, String age) {
            this.ID = new SimpleStringProperty(ID);
            this.press = new SimpleStringProperty(press);
            this.age = new SimpleStringProperty(age);
        }

        public String getID() {
            return this.ID.get();
        }

        public String getPress() {
            return this.press.get();
        }

        public String getAge() {
            return this.age.get();
        }

    }

    /**
     *
     * Class for tableview items only.
     */
    public static class MiscValues {

        private final SimpleStringProperty name;
        private final SimpleStringProperty val;

        private MiscValues(String name, String val) {
            this.name = new SimpleStringProperty(name);
            this.val = new SimpleStringProperty(val);
        }

        public String getName() {
            return this.name.get();
        }

        public String getVal() {
            return this.val.get();
        }

    }
}
```

APPENDIX 3

GAMS LINEAR PROGRAMMING CODE

Model input

SETS   K   1 pump   /PUMP1/

         M   4 pipe sizes   /PS12, PS8, PS10, PS6/

         N   20 arcs   /N186, N194, N198, N200, N201, N202, N203, N204, N205, N206, N207, N208, N209, N211, N212, N213, N214, N1, N2, N4/

         D   20 delivery points   /DP59, DP74, DP103, DP104, DP119, DP120, DP122, DP123, DP146, DP125, DP126, DP130, DP137, DP145, DP151, DP156, DP157, DP158, DP159, DP3/

PARAMETER CPUMP(K)

     /PUMP1   0.072/;

PARAMETER CPIPE(M)

     /PS12   27.3

      PS8   17.86

      PS10   22.68

      PS6   13.42/;

PARAMETER RHS(N)

```
    /N186              199.47
N194              257.06
N198              397.08
N200              450.07
N201              112
N202              179.79
N203              332.58
N204              197.2
N205              879.55
N206              136.23
N207              583.34
N208              98.97
N209              199.15
N211              537
N212              182
N213              158
N214              127
N1            1190
N2            1
N4            96.89/;
```

PARAMETER RHSS(D)

```
    /DP59              86.1331747
DP74              86.1331747
DP103              120.1331747
DP104              128.1331747
DP119              129.1331747
DP120              86.1331747
DP122              68.1331747
DP123              51.1331747
DP125              48.1331747
```

DP126	47.1331747
DP130	42.1331747
DP137	36.1331747
DP145	36.1331747
DP146	88.1331747
DP151	89.1331747
DP156	69.1331747
DP157	61.1331747
DP158	52.1331747
DP159	46.1331747
DP3	79.1331747/;

PARAMETER RHSSK(D)

/DP59	178.399524
DP74	178.399524
DP103	212.399524
DP104	220.399524
DP119	221.399524
DP120	178.399524
DP122	160.399524
DP123	143.399524
DP125	140.399524
DP126	139.399524
DP130	134.399524
DP137	148.399524
DP145	148.399524
DP146	180.399524
DP151	181.399524
DP156	161.399524
DP157	153.399524
DP158	144.399524

DP159   138.399524

DP3   171.399524/;

PARAMETER Q(N)

    /N186   0.119262

N194   0.106898

N198   0.069762

N200   0.067298

N201   0.047498

N202   0.042548

N203   0.034254

N204   0.025982

N205   0.017732

N206   0.00946

N207   0.001188

N208   0.101948

N209   0.084612

N211   2.321198

N212   2.324146

N213   2.327094

N214   2.330042

N1   2.318712

N2   2.332968

N4   0.007436/;

PARAMETER DIN(M)

    /PS8   8

     PS10   10

     PS12   12

     PS6   6/;

TABLE DUMP(K, D)

	DP59	DP74	DP103	DP104	DP119	DP120	DP122	DP123	DP125	DP126	DP130	DP137	DP145	DP146	DP151	DP156	DP157	DP158	DP159	DP3
PUMP1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1;

TABLE DUMJ(D,N)

	N186	N194	N198	N200	N201	N202	N203	N204	N205	N206	N207	N208	N209	N211	N212	N213	N214	N1	N2	N4
DP59	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0
DP74	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0
DP103	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0
DP104	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0
DP119	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0
DP120	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0
DP122	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0
DP123	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	0
DP125	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	0
DP126	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	0
DP130	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	0
DP137	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0
DP145	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0

```
DP146  1    1    0    0    0    0    0    0    0    0    0    1    0    1    1
1    1    1    1    0

DP151  0    0    0    0    0    0    0    0    0    0    0    0    0    1    1
1    1    0    1    0

DP156  0    0    0    0    0    0    0    0    0    0    0    0    0    0    1
1    1    0    1    0

DP157  0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
1    1    0    1    0

DP158  0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    1    0    1    0

DP159  0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    1    0

DP3    1    1    1    1    0    0    0    0    0    0    0    1    1    1    1    1
1    1    1    1 ;
```

```
VARIABLES          X(N,M)
          XP(K)
          COST;


POSITIVE VARIABLE     X;
POSITIVE VARIABLE     XP;



EQUATIONS          LENGTH(N)
          HYDRAULIC(D)
          HYDRAULICK(D)
          MINCOST;


LENGTH(N)..SUM(M,X(N,M))=E=RHS(N);
HYDRAULIC(D)..SUM(K,DUMP(K,D)*XP(K))
```

-

SUM(N,SUM(M,DUMJ(D,N)*(0.00012586*Q(N)**2/(DIN(M)/12)**5)*X(N,M)))=g=RHS
S(D);

HYDRAULICK(D)..SUM(K,DUMP(K,D)*XP(K))

-

SUM(N,SUM(M,DUMJ(D,N)*(0.00012586*Q(N)**2/(DIN(M)/12)**5)*X(N,M)))=L=RHS
SK(D);

MINCOST..SUM(K,CPUMP(K)*XP(K))   +   SUM(N,
SUM(M,CPIPE(M)*X(N,M)))=E=COST;

MODEL dualone_mydata2 /ALL/;

SOLVE dualone_mydata2 USING LP MINIMIZING COST;

DISPLAY X.L, XP.L, COST.L;