ANALYSIS OF THE RESILIENCE OF INTERMITTENT WATER SUPPLY SYSTEMS AND THE DISRUPTION-DYNAMICS OF STAKEHOLDERS

by

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A Dissertation

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Doctor of Philosophy

Lyles School of Civil Engineering

West Lafayette, Indiana

August 2020

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To my parents,

Who gave me more than what I asked for

To my wife, Sumaiah

Whose love and support are more than what I can be thankful for

To my kids, Hatoon and Ibrahim

Who are the lights in my life

ACKNOWLEDGMENTS

I would like to thank my doctoral advisor, Professor Dulcy Abraham, for her endless guidance, support, and patience during my graduate studies at Purdue University.

I would like to also thank my Ph.D. committee members, Professor Dan DeLaurentis, Professor Tom Iseley, Professor Suresh Rao, and Professor David Yu, for their support and guidance throughout my Ph.D. studies.

I am grateful for the love, support, and prayers of my parents, my family, and my kids. My special thanks and gratitude go to my wife, Sumaiah. Her support, encouragement, and patience were the sources of my strength throughout my journey at Purdue.

I would like to thank my friends and colleagues at Purdue, who provided their support and help in navigating graduate school.

This work would not have been accomplished without the support of my country, the Kingdom of Saudi Arabia, which fully sponsored my graduate studies. I would also like to thank my employer, King Saud University, which offered me a scholarship to obtain my Ph.D. degree from Purdue and supported me in gathering the data and conducting the research for this dissertation. I would like to especially thank Professor Khalid Alqahtani for his guidance and assistance during my Master's and Ph.D. studies at Purdue.

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ABSTRACT

Millions of households around the world rely on intermittent water supply systems (IWS), where piped water supply is limited to specific hours during the day or on specific days during the week. Households relying on IWS systems, as their primary water source, often adapt to supply intermittency by installing in-house water storage and/or supplying water from non-piped sources (for instance, in the form of water tanker trucks). The piped water distribution network (WDN) in IWS systems is subject to short-term disruptions that cause dynamic behavior and interactions of the system's stakeholders, including households, vendors of non-piped water, and the water utility. During disruptions of the WDN, households make decisions about obtaining water from different non-piped sources at different prices and wait times. These decisions, made by a large number of households, have an impact on the dynamics (in particular, the prices and availability) of the non-piped water market, which may in turn affect each household decision. Prior studies on the literature of the analysis of IWS systems focused on analyzing each of the components (namely the WDN, households, vendors of non-pied water, and the water utility) of the IWS in isolation, assuming static behavior of the other components.

The overreaching objective of this dissertation is to bridge the gap in knowledge and practice in analyzing the short-term dynamics within each component of the IWS system (focusing on the WDN and the households) and the interactions among all components of the IWS system when responding to physical disruptions of the WDN. First, a new framework for quantifying and analyzing the resilience of intermittent WDNs is presented. The framework incorporates the aspects of intermittent supply (including household storage and supply scheduling) into a hydraulic model that examines the network's hydraulic performance and its topology to assess three resilience capacities: absorptive, adaptive, and restorative, against various types of physical disruptive events. The evaluation of the model, using the IWS network of a case study city in the Middle East, shows that household storage capacities, timing and length of the disruption, supply inequity, and the supply scheduling are significant factors in determining the resilience of the WDN, and the interactions of these variables result in different combinations of direct and post effects on households. The framework was also used to evaluate the impact of temporary modifications of the supply schedule on the network's resilience. The results show that this short-

term utility adaptive measure can significantly improve the resilience of the network. The proposed framework can assist utilities in the operation of the intermittent WDN under normal conditions and in the evaluation of the impact of different short- and long-term resilience enhancement strategies.

Next, based on empirical data from a survey of households in a city in the Middle East, the households' decision-making in response to disruptions of the WDN was evaluated using econometric methods. A set of Binary Probit models were developed to model the decision of households regarding their risk attitudes toward running out of water (represented by the timing of their response actions), their willingness to pay for faster delivery of non-piped water, and their willingness to wait in-line to obtain water from a non-piped source. The results show how variables related to household characteristics, wealth, age and occupation of the household's manager, knowledge of household manager about their households' water situation, and prior experience with disruptions affect the households' decisions when the piped-network is disrupted. The outputs of the econometric models can assist the city's water managers in understanding the behavior of households that affect the demand and prices of different non-piped water sources.

The final component in this research integrates the two previous components into an Agent-Based Model (ABM) to evaluate the dynamics of the stakeholders' interactions in response to disruptions of the WDN and to evaluate the impact of these interactions on the resilience of the whole system. The ABM examines the interactions between households and vendors of water tankers under utility's policies that regulate the water tanker market while integrating variables that describe the response of the WDN to the disruption. The demonstration of the model using a representative subset of the IWS system in the case study city shows dynamic behavior patterns in: (a) the dynamics of households, and (b) the performance of the non-piped water market under different deterministic and stochastic scenarios of disruptions of the WDN.

The results of this research address many IWS systems in the Middle East and around the world that are characterized by household storage, as well as households' dependency on the piped network as the main water supply. The models developed in this dissertation are expandable to adopt various systems' configurations in terms of types and capacities of household storage, types and attributes of non-piped water sources, and attributes and preferences of households. The results of this doctoral research can assist water managers in cities in understanding the behavior of their IWS system (including the WDN and the system's stakeholders), evaluating long-term resilience enhancement policies, and planning for short-term response to disruptions of the WDN.

1. INTRODUCTION

The Urban Water Supply Infrastructure System (referred to as the Piped Water Distribution Network WDN) is the physical system that derives and pumps water from sources such as reservoirs and groundwater, treats it, transports it, and distributes it through a piped network for residential, commercial, and some industrial purposes. It includes treatment plants, pumping stations, pipelines, valves, storage tanks, and supporting control and monitoring systems that are essential for the operation of water treatment, transporting, and distribution. The WDN is one of the critical infrastructures identified by the Homeland Security and national disaster management plans. Other critical infrastructures (e.g., electric generation, healthcare, etc.) depend on water supply for their operation. According to a U.S. Department of Homeland Security study in 2014, the services of other critical infrastructures are degraded by more than 50% within 8 hours of losing drinking water supply (DHS 2014). After the terrorist attacks of September 11, 2001, Hurricane Katrina in 2005, Superstorm Sandy 2012, and other significant disasters, the study of the resilience of critical infrastructures (including water supply infrastructures) has garnered increased attention as part of a larger strategy for homeland security.

The Urban Water Supply System (WSS) is a broader system that includes the physical water network, its operation and management, and the behavior of the users of its services. In addition, the WSS includes non-piped potable water supply modes, such as private wells, mobile tankers, and bottled water. Hence, the WSS includes the WDN, other supply modes, and the stakeholders, including water consumers, water utility, and entities in the market for non-piped drinking water.

Urban water supply systems in many parts of the world, especially in developing countries, face many challenges in supplying water continuously (i.e., for 24 hours, 7 days a week) to their consumers. Alternatively, utilities use an intermittent water supply strategy to adapt to these challenges. Intermittent Water Supply Systems (IWS Systems) are defined in this research as piped water distribution systems that supply water to their customers for less than 24 hours a day or less than 7 days a week under normal operating conditions. This definition implies that the intermittency of supply in the IWS systems is a chosen strategy by the system operator (i.e., the water utility) due to obstacles that prevent continuous water supply.

More than 1 billion people around the world are supplied by intermittent water supply (IWS) piped systems that provide water intermittently (Kaminsky and Kumpel 2018). Klingel (2012) roughly estimated the percentages of the water supply systems that operate intermittently in different parts of the world to be 30% in Africa, 50% in Asia, 60% in Latin America, 90% in Southeast Asia, and almost 100% in India. IWS systems are often designed to supply water continuously in the first place, but they are operated under IWS due to economic, ecological, technical, and/or institutional obstacles (Klingel 2012). The predominant cited reason for these IWS system is the scarcity of water resources. However, other factors (such as those related to the behavior of consumers, local governance, and financial constraints) also play a significant role in causing or reinforcing intermittent supply (Galaitsi et al. 2016).

1.1 Research Motivation

The analysis of IWS systems is different from the analysis of water supply systems with continuous water supply (CWS) due to several reasons. In terms of the analysis of the water network (WDN), the traditional analysis approaches of CWS systems cannot be used for the hydraulic analysis of IWS systems due to the existence of features unique to the IWS, such as the periodic filling and emptying cycles of pipes, the significant fluctuations in pressure, and the existence of local household water storage. In addition, the analysis of the behavior of consumers is different and more complicated in IWS systems. Consumers often adapt to the intermittency in water supply by storing water, supplying water from other sources, and changing their water use patterns to adapt to the water supply. Furthermore, many IWS systems in developing countries have unconnected consumers, illegal connections, and no water metering. Therefore, the analysis of WSS systems with intermittent supply requires the consideration of other non-piped water supply sources, the dynamic behavior of different types of consumers, and special hydraulic considerations.

1.2 Problem Statement

The disruption of the piped water network causes more dynamic changes in the behavior of the system stakeholders in IWS systems compared to CWS systems, since stakeholders in IWS systems have a wider range of adaptive actions they can choose from to manage their temporary situation. Consumers of CWS systems often do not have local water storage, and they have very limited access to non-piped water sources during times of disruption. The main disruption-response action available to consumers in CWS systems is water conservation. Similarly, the utility behavior during disruptions of CWS systems is limited to the restoration efforts of the system components.

Prior research efforts on the analysis of the resilience of WDN (the piped network) are limited to continuous water supply. In addition, current resilience analysis frameworks do not include the dynamic behavior of consumers and assume static demand patterns before and during disruptions. Consumer behavior and utility actions are even more dynamic (in terms of obtaining non-piped water) in the case of IWS. Furthermore, even without considering the dynamic behavior of stakeholders, current resilience analysis frameworks that are developed for CWS cannot be used in the case of IWS due to the major differences in the network operation and the existence of unique components.

1.3 Research Questions

This research aims to answer questions related to the analysis of the resilience of IWS systems and the behavior of the systems' stakeholders during disruptions. The following research questions are addressed in this dissertation:

- How can the resilience of WDN, in the context of IWS, be quantified? What system performance measures can explain the system behavior at all stages of the disruption-recovery cycle? What metrics can explain the *contribution* of each resilience capacity to the overall system's resilience?
- As an adaptive resilience measure, what is the effectiveness of modifying the utility's supply schedule during system disruptions?
- What are the factors that affect the decision-making of households in IWS systems related to obtaining non-piped water in response to disruptions?
- What are the dynamics of the interactions between the system's stakeholders during disruptions? How is community resilience affected by these dynamics?

1.4 Research Hypotheses

This research evaluates three main hypotheses related to the resilience of IWS systems under short-term disruptions:

1. IWS systems can be robust against short-term acute disruptions due to the available buffer in the form of local household storage. However, their robustness depends on household storage capacity, the level of supply inequity, and the intensity and the length of the disruption.
2. When obtaining non-piped water during disruptions, households are heterogeneous in terms of their preferences regarding the risk of running out of water, their willingness to pay for faster delivery, and their willingness to pay for convenient non-piped sources. In addition, the knowledge and the awareness of the household manager about their water situation and their previous experience with the multi-mode water supply system have an impact on their preferences related to obtaining non-piped water.
3. The behavior of stakeholders in the IWS system is affected by the dynamics of the WDN where the network supply to consumers changes throughout the duration of the disruption, and the dynamic interactions between stakeholders during system disruptions may result in emergent behavior in the system.

1.5 Research Objectives

To address these research questions, the following research objectives were developed:

1. Develop and evaluate a framework for assessing and quantifying the resilience of physical water infrastructure systems within the context of IWS
2. Evaluate the short-term behavior of consumers during physical disruptions in the piped water network
3. Evaluate the dynamics of the interactions of stakeholders (consumers, utility, and entities in the non-piped water market) during disruptions in the piped network and the impact of those interactions on the resilience of the system

1.6 Research Scope and Boundaries

Figure 1.1 explains the interactions between the four main components of the IWS system (namely, piped distribution system, water manager/operator, water consumers, and the market of non-piped water) during both normal operations and during disruptions of the physical infrastructures.

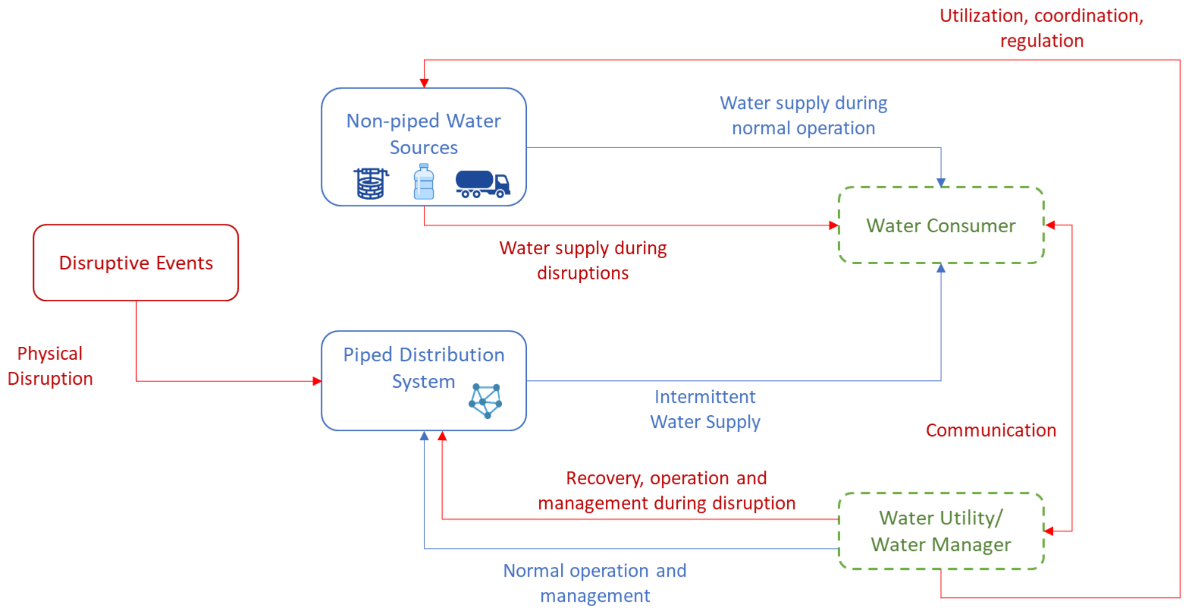


Figure 1.1. Problem Boundaries (Arrows represent the relationships between components, blue: during normal operation, red: during disruptions)

IWS systems can have various configurations based on different supply schemes (i.e., mechanisms to distribute the supply between different parts of the network) and consumers' adaptations (e.g., types of water storage, water conservation). This dissertation focuses on IWS systems that are characterized by local household storage with greater consumer dependence on the piped network, and evaluates the resilience of IWS networks against acute physical network disruptions. Additionally, it addresses the short-term behavior of the stakeholders of IWS systems in response to these disruptions. The following subsections define the terms *resilience*, *disruptive events*, and *stakeholders' behavior*, and explain the scope of this dissertation.

1.6.1 Resilience of Water Supply Infrastructure Systems

There is no universal definition of the term *resilience*, and across research disciplines, there are many definitions and perceptions of resilience. In the field of physical infrastructures, resilience is defined as “The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions” (Presidential Policy Directive/PPD–21 2013). Similarly, the National Infrastructure Advisory Council defines infrastructure resilience as the “ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event” (National Infrastructure Advisory Council 2016). These definitions address three different capacities of resilience: Absorptive, Adaptive, and Restorative/Recovery resilience (Francis and Bekera 2014):

- *Absorptive capacity* is the degree to which a system can absorb the impacts of system perturbations and minimize consequences with little effort (Vugrin et al. 2010). Pre-disruption characteristics of the system, such as robustness and reliability, are used to represent absorptive capacity. Designing a system with a buffer capacity, for example, addresses the absorptive capacity of the system (Francis and Bekera 2014).
- *Adaptive capacity* is the ability of the system to undergo some changes to adjust to undesirable situations, and it differs from absorptive capacity in that adaptive systems undergo changes in response to disruptions, especially if absorptive capacity has been exceeded. An adaptive system is a system that is prepared for adverse events and that is able to anticipate disruptions, recognize unanticipated shocks, and re-organize after the occurrence of a disruptive event (Francis and Bekera 2014).
- *Restorative capacity* is the rapidity of return to normal or an improved level of performance and system reliability. It is usually assessed against a predefined desirable level of service.

This dissertation has adopted the approach of conceptualizing the resilience of the WDN using three resilience capacities: *Absorptive*, *Adaptive*, and *Restorative*.

Physical infrastructures by themselves can only have robustness/resistance (in the form of redundancy, buffer capacity, and strength), and they cannot have *resilience* in the sense of adaptation or recovery. *Resilience* is provided by utilities and households who have the capacity to implement adaptive strategies to cope and recover from failures (Krueger et al. 2019). Hence, this research evaluates the resilience of IWS systems at two levels: *operational resilience* and *community resilience*. Operational resilience includes the built-in robustness/resistance of the physical WDN and the adaptive behavior of the utility required for recovering from disruptions. Long-term households’ adaptations, in the form of water storage, are considered as part of the built-in robustness of the WDN. On the other hand, community resilience integrates operational resilience with the short-term adaptive behavior of households in response to disruptions (e.g., obtaining non-piped water). In other words, operational resilience assumes the absence of short-term adaptations of households, while community resilience considers the inclusion of households' short-term adaptations. Operational resilience is of interest to the utility in terms of the technical operation of the network, and it provides insights about the operation of IWS networks during disruptions. On the other hand, community resilience is of interest to the city's water managers (which can be the utility or the city) to assess the impact of the network disruption on households considering other modes of water supply. Figure 1.2 provides an illustration of the scope of the two levels of resilience, showing the components of the IWS system and their interactions.

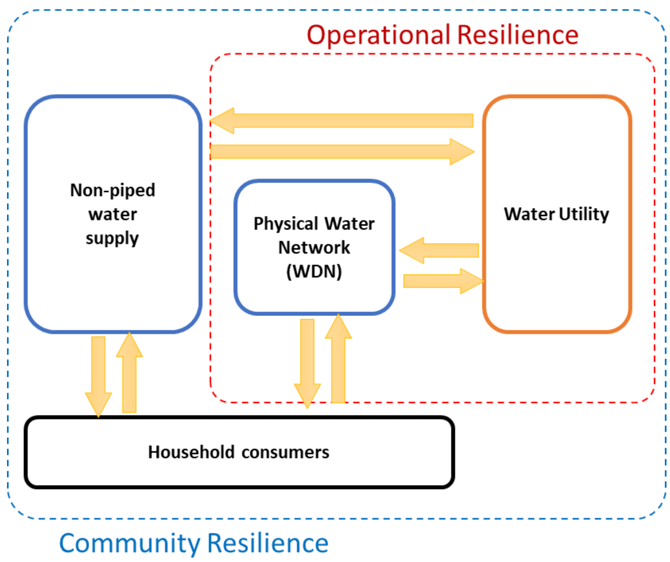


Figure 1.2 Illustration of the components of the IWS system and their interactions for the operational resilience and the community resilience

Disruptive Events

The resilience of WDN is assessed against disruptive events (equivalent terms used in the literature include hazards, threats, shocks, perturbations, disturbances, and disasters). Disruptive events of the WDN can be physical or non-physical. *Physical* disruptive events include:

1. Random failures: a collective name for the failures of system's components due to aging, accidents, human errors, equipment failures, or triggered by vegetation (trees) or animals (Ouyang et al. 2012)

2. Natural hazards (such as earthquake, hurricanes, floods, etc.)
3. Deliberate attacks: planned attacks that target parts of the system (e.g., terrorist attacks)
4. Cascading failures: failure of physical components due to capacity exceedance when the flow is redistributed following a disruption triggered by other events
5. Interdependence effects: perturbations caused by failures on another system that transfer to the system of interest due to the interdependence relationship

Non-physical disruptive events include community-based disruptions and economic shocks. An example of community-based disruptions is the change in households' water-related behaviors that affects the water demand patterns. Another example of community-based disruptions is the dramatic changes in served population that either put more pressure on the infrastructure system in the case of dramatic increase in population (e.g., people arriving to a city fleeing from a natural disaster) or making the operation of the whole system financially stressful in the case of dramatic declining in population (e.g., shrinking cities (Faust et al. 2016)). Economic shocks impact financing and budgeting the operation, maintenance, and enhancement of the water supply infrastructure. One distinction between physical and non-physical disruptive events that has implications on resilience analysis is that non-physical disruptions usually occur over longer periods of time (since they are usually indirect) compared to physical disruptive events. Physical disruptive events occur within seconds, minutes, or hours, whereas the impacts of non-physical events may take days, years, and sometimes decades to manifest on system performance.

The focus of this research is the analysis of the impacts of *physical* disruptive events on the resilience of IWS systems. Disruptive events can be classified as *initial* (random failures, natural hazards, and deliberate attacks) and *secondary* (cascading failures and Interdependence effects). Initial disruptive events are hazards whose occurrence and level of intensity are independent of the condition of the system. Secondary disruptive events are triggered by changes in the condition of the WDN (i.e., cascading failures) or the condition of the infrastructure system upon which the WDN depends on (i.e., interdependence effects). This research currently addresses initial (direct) disruptive events, but it can be expanded to include secondary disruptive events.

1.6.2 Behavior of IWS Systems Stakeholders

The key stakeholders of the IWS system considered in this research are:

- Water Manager: includes the water utility that is responsible for the operation and management of the physical water distribution network and/or, in some cases, the operation and management of other modes of water distribution (e.g., water tankers). In some cases, the water manager may also include governing entities that are responsible for water planning and policies.
- Stakeholders in the Market Non-piped Water: includes entities in the informal market of residential potable water in the form of water tankers, bottled water, and other forms of water supply that are not provided by the water utility. This component includes regulated and unregulated (or sometimes illegal) residential water markets.
- Water Consumers: the residential users of the water who receive the service from the water utility and/or buy the water from the private water market for household uses.

The behavior of stakeholders in the IWS system can be analyzed in the long term and in the short term. The long-term analysis considers the actions of the stakeholders to manage their future situations based on their past experience with the system. On the other hand, the short-term analysis considers the actions of system stakeholders to manage their current situations without necessarily considering improvements to their future conditions. Consumers in IWS systems take long-term and short-term water management actions to adapt to the intermittency in the water supply. Long-term actions are in the form of investment decisions in water storage, water conservation, and water supply, to manage consumers' water supply and consumption in the future. Long-term decisions are often costly and have a lasting effect on the consumer's water situation (i.e., for months or years). On the other hand, short-term actions are temporary decisions that aim to manage the consumer's day-to-day water supply and demand. Short-term actions improve the consumer's water situation only for several days (or weeks at most). The water manager also makes long-term (e.g., investing in water storage, changing water tariffs, or investing in increasing the capacity of the system) and short-term decisions (e.g., modifying supply durations or schedules in response to available water resources). Similarly, stakeholders in the market of non-piped water respond to the long-term and short-term changes in demand by changes in the price, availability, and capacity of the private market. This dissertation addresses the short-term behavior of the stakeholders in IWS systems in response to physical disruptions of the piped network.

1.7 Research Overview

Figure 1.3 describes the research activities to achieve each research objective. The inputs, outputs, and processing research tools are described for each activity. A framework for quantifying and assessing the resilience of IWS systems is developed by building a resilience quantification model using tools of hydraulic modeling and graph theory. The framework is then evaluated using a case study of a real IWS network. The IWS resilience model is then used to evaluate the adaptive utility operational actions on the piped network during disruptions.

Furthermore, the research analyzes the consumers' short-term decision making in response to network's physical disruptions. Using the results of a developed household survey, consumers' behaviors are modeled using econometric methods (Binary Probit Models). The final component of the research integrates the outputs of the other components to analyze the dynamics of the interactions between the IWS system's stakeholders using an Agent-Based Model, and to assess the effects of these dynamics on the resilience of the system.

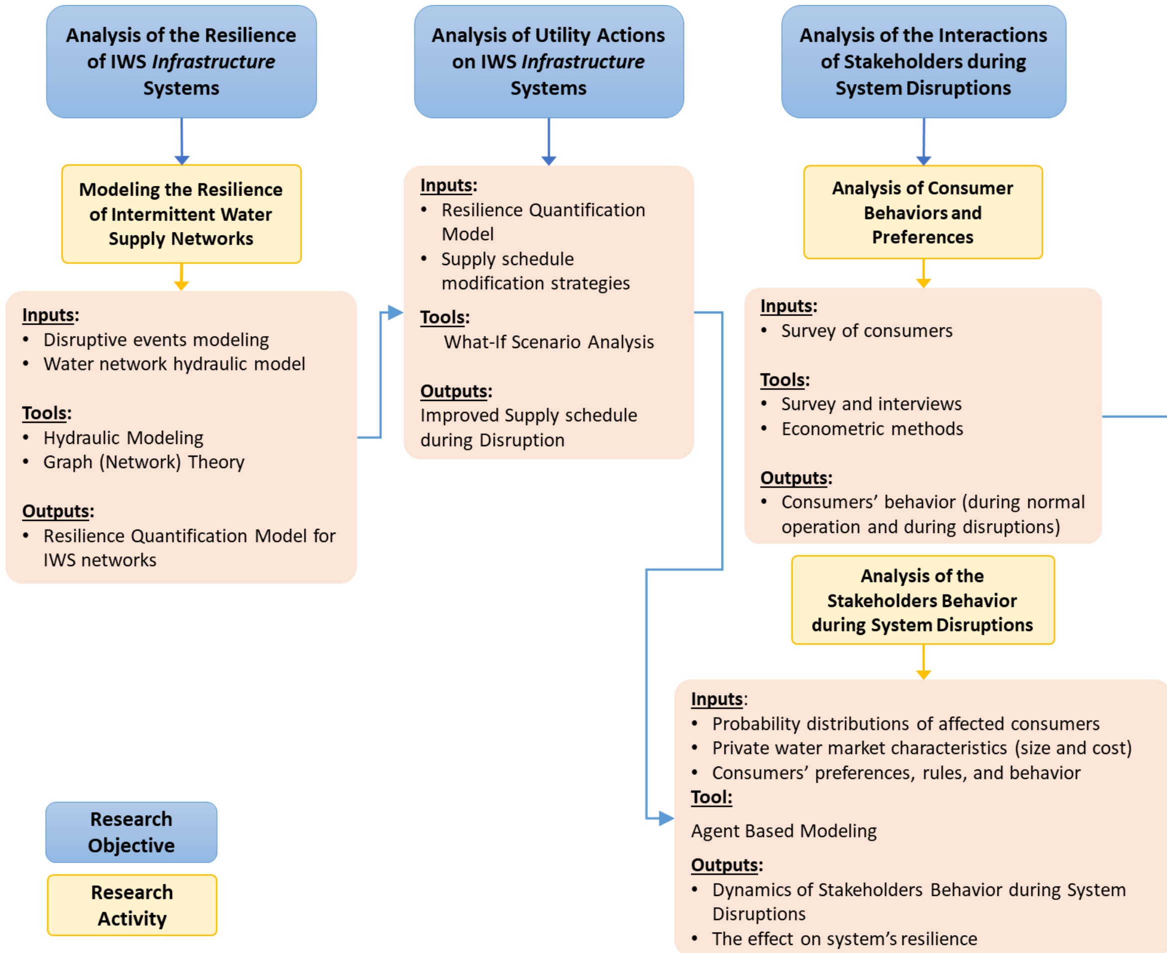


Figure 1.3. Research Framework

1.8 Description of the Water System Testbed

The research components of this dissertation are developed/evaluated within the context of a case study of a subnetwork from the water supply network in a city in the Middle East. The city is located at the center of the country and at an elevation of 612 m (2008 ft). The city is approximately 1800 km^2 (700 sq mi) in area, with a population of about 8 million. There are approximately 1.3 million households in the city, with an average size of 5.9 people per household. The per capita average daily water consumption is one of the highest in the world at 350 liters (around 94 gallons). The city is located in a hot and dry region with low average annual precipitation of around 100 mm (3.94 in). Hence, the city has no surface water resources, and 60% of the city's supply comes from desalination plants at the seacoast (located at almost 450 km (280 mi) from the city) while the remaining 40% of the demand is supplied by groundwater from government-owned wells.

Water consumers in the city receive their water supply through the piped network that is owned and operated by the water utility. Due to the limited water resources, the utility has long adopted intermittent water supply by alternating the supply between zones in the network following weekly schedules. Consumers have adapted to the supply intermittency by installing/constructing in-house water storage tanks with various capacities. Almost 100% of the households in the city have some type of water storage tank.

1.9 Dissertation Organization

This dissertation consists of five chapters and follows the "multiple publications" format. Each of the Chapters 2, 3, and 4 has its own introduction, literature review, methodology, results and discussion, and conclusion sections. Significant portions of these chapters have been submitted or are in preparation for submission for review and publication in peer-reviewed journals and/ or refereed conferences. Chapter 1 includes the introduction of the dissertation and discusses the research motivation, the problem statement, and research objectives. Chapter 2 introduces a new framework for the assessment of the resilience of intermittent water supply infrastructure systems and discusses the implementation of the framework in the context of the IWS system in the case study city. ***This chapter is reprinted in part from the conference paper published in the ASCE Construction Research Congress 2018, Saad I. Aljadhai, Dulcy M. Abraham, Quantifying the Resilience of Water Supply Infrastructure Systems: The Role of Infrastructure Interdependency, pp. (496-506). Tables and figures captions were modified to maintain the form of the dissertation.***

Chapter 3 analyzes households' decision-making behavior in response to disruptions in the water distribution network. This chapter models the preferences-related households' decision-making and discusses the factors that affect households' decisions regarding obtaining non-piped water. ***A version of this chapter was published in the proceedings of ASCE World Environmental and Water Resources Congress 2020, Saad I. Aljadhai, Dulcy M. Abraham, Modeling Dynamic Consumer Decision during Disruptions of Intermittent Water Supply Systems, pp. (360-373). Tables and figures captions were modified to maintain the form of the dissertation.***

Chapter 4 discusses the evaluation of the dynamics of the interactions between the stakeholders of the IWS system in response to the disruptions of the water distribution network. This chapter discusses the Agent Based Model developed to model and evaluate the dynamics and the interactions of stakeholders of the IWS system, and it discusses the results of the model implementation in the context of the IWS system in the case study city. Chapter 5 presents the conclusions of the dissertation, the contributions to the body of knowledge and practice, the limitations of the current research, and recommendations for future research.

2. RESILIENCE ANALYSIS OF INTERMITTENT WATER SUPPLY INFRASTRUCTURE SYSTEMS

[Sections of this chapter were published in the proceedings of the ASCE Construction Research Congress 2018.][1]

This chapter introduces a new framework for quantifying and evaluating the resilience of IWS infrastructure networks (i.e., WDN) and their operation against network physical disruptions. Resilience quantification is important to guide network resilience enhancement strategies done by the network manager (i.e., the utility). Resilience metrics can be used for evaluating the effectiveness of different resilience enhancement strategies for both short term (e.g., temporary operational modifications) and long term (e.g., designing new parts of the network or modifying the current network). As discussed in Section 1.1, analyzing the resilience of IWS infrastructure networks requires unique hydraulic and performance assessment considerations due to the way these networks operate (i.e., periodic filling and emptying cycles of pipes, significant fluctuation in pressure) and unique consumer adaptive behaviors (i.e., local household water storage).

The resilience of the IWS network depends on both the network configuration (i.e., network components and topology) and its operational management. The behavior of the utility plays an important role in the resilience of the water network. In CWS networks, the utility's adaptive response to network disruptions is limited to restoring the damaged network components (e.g., damaged pipes) and limited temporary flow diversions. However, more options are available to the utility in the case of IWS since many IWS networks operate with available buffer in the system (in the form of household water storage). This storage buffer gives the utility more room to modify the operation of the network to maximize its performance since network supply can be diverted from households with available stored water to the affected parts of the network. The option of modifying supply schedules to maximize the network's resilience is an idea that has not been investigated in prior research.

[1] Aljadhai, S. and Abraham, D. (2018). "Quantifying the Resilience of Water Supply Infrastructure Systems: The Role of Infrastructure Interdependency". *Construction Research Congress 2018*. New Orleans, LA. (pp. 496-506) (With permission from ASCE).

This chapter introduces a new framework for quantifying the resilience of IWS infrastructure networks (Research Objective 1.a). The framework assesses three resilience capacities; *absorptive*, *adaptive*, and *restorative* against physical disruptive events. In addition, the short-term adaptive behavior of the utility during network disruptions (in the form of supply schedule modifications) is modeled, and its impact on operational resilience of the network is evaluated (Research Objective 1.b)

First, a discussion of the prior work on analyzing the resilience of water supply networks (developed for CWS systems) and prior work on analyzing IWS networks is presented to highlight the existing gaps related to the resilience assessment of IWS networks. Second, the methodology for the proposed resilience assessment framework is discussed. The resilience framework is then implemented and evaluated within the context of a real water network. Finally, the operational resilience of the utility is addressed by analyzing the utility's adaptive measures to enhance the performance of the network during disruptions. Different proposed strategies for modifying the supply schedule are evaluated and their impact on the network's resilience is assessed.

2.1 Literature Review

This section gives an overview of the prior research on resilience assessment of water supply networks (for CWS) to define the existing gaps in resilience quantification for water supply networks. It also gives an overview of the prior research on the analysis of water networks in the context of IWS to highlight the absence of consideration of network disruptions in prior studies.

2.1.1 Prior Research in Resilience Assessment for Water Supply Networks[2]

An examination of the literature in the resilience assessment of infrastructure systems suggests that resilience assessment frameworks are developed to achieve different objectives. These objectives include identification of vulnerable components in the system, quantification of overall-system vulnerability, testing resilience improvement strategies, investigating the effect of interdependencies, and/or effectively quantifying the system's resilience.

[2] Section adapted from Aljadhai and Abraham (2018)

Resilience quantification is a common important step in the development of most frameworks that address infrastructure resilience. There are *three* main general approaches to quantify the resilience of critical infrastructures. The *first* approach quantifies the resilience by measuring the loss of infrastructure performance due to disruptions. The performance of the water network can be measured by many metrics (e.g., pressure, number of affected nodes, and water quality). In this approach, a resilient system is a system that minimizes the impacts of disruptions on the system's performance (by reducing the failure consequences and/or recover rapidly from disruptions). Studies that have used this approach usually measure the loss of system performance by:

(1) comparing the system performance before and immediately-after the disruption (applied for absorptive and adaptive capacities) (Gay and Sinha 2012; Francis and Bekera 2014);
(2) comparing the disrupted infrastructure performance to the original performance at different times during the disruption (Francis and Bekera 2014); or
(3) calculating the area between the targeted (original) performance curve and the disrupted performance curve (Vugrin et al. 2010; Ouyang et al. 2012; Ouyang and Dueñas-Osorio 2012) (Figure 2.1).

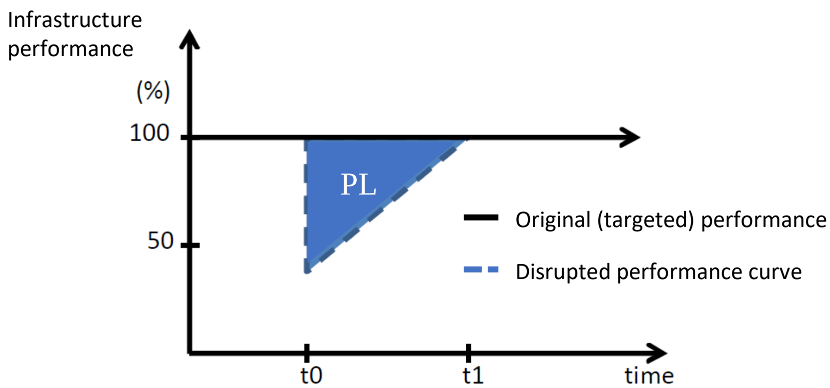


Figure 2.1. Conceptual illustration of the area that represents the performance loss (PL) (*adopted from: Vugrin et al. 2010*)

The *second* approach is a probabilistic approach where the resilience is measured as the probability that the system will meet pre-defined standards (Chang and Shinozuka 2004; Gay and Sinha 2012). These standards can be related to the loss of system performance (e.g., maximum acceptable performance loss) or related to the system's recovery efforts and time (e.g., maximum acceptable recovery time and/or cost).

The *first* and *second* approaches measure the resilience in terms of how the system output is affected by disruptions. However, in the *third* approach, system resilience is measured as the system's vulnerability to disruptions (Adachi and Ellingwood 2008; Yazdani and Jeffrey 2012; Wang et al. 2012; Farahmandfar et al. 2015). In this approach, a more resilient WDN is a system whose characteristics make it less vulnerable to disruption. Prior studies of this approach focused on one or more of the following system's attributes:

a) components' conditions (for instance, condition of pipelines),
b) topology,
c) hydraulic characteristics,
d) and/or interdependencies configurations

Table 2.1 summarizes the approaches of prior research and their methods or focus. Most of the quantification frameworks in the literature in the resilience of water supply infrastructure systems address only one or two of the three resilience capacities (i.e., absorptive, adaptive, and restorative) and/or limited to one specific disruptive event. Even though few frameworks addressed all resilience capacities (e.g., Vugrin et al. 2010; Ouyang et al. 2011, 2012; Francis and Bekera, 2014; Guidotti et al. 2016), the resilience metrics used cannot explain the contribution of each resilience capacity. For instance, the quantification method of *the area of the deviation from the targeted performance curve* (as in Figure 2.1) captures all resilience capacities; however, it gives a combined value that cannot explain which capacity has a greater or lesser contribution towards system resilience. Identifying the contribution of each capacity is important to guide resilience enhancement decisions and efforts. On the other hand, quantifying each capacity separately might lead to missing some resilience effects (i.e., interdependencies between and among resilience capacities). There is a need for the integration of multiple methods that can jointly explain the resilience of the system and the contribution of each resilience capacity.

There is also a need to incorporate the appropriate system performance measures that explain the system behavior at each stage of the system's response cycle (i.e., disaster prevention → damage propagation → recovery). For example, using measures such as the *proportion of surviving nodes*

(Adachi and Ellingwood 2008; Ouyang et al. 2012) or *proportion of nodes that meet a threshold* (Guidotti et al. 2016) to assess the system performance cannot explain the system response to disruptive events in a situation where the system has a buffer that absorbs the shock and all nodes survive or meet the threshold. In this case, other performance measures such as the *average surplus nodal head* (Farahmandfar et al. 2015) can capture the pressure drop and explain how the system prevented service loss at demand nodes. A combination of two or more measures might be helpful since each measure may explain more about a particular stage of the system's response cycle.

Table 2.1. Summary of Approaches of Prior Research in Resilience Assessment for Infrastructure Systems

Study System(s) – disruptive event(s) addressed	***(Approach 1)*** Analysis of performance loss	***(Approach 2)*** Probability of meeting pre-defined standards	***(Approach 3)*** Vulnerability-based analysis
Chang and Shinozuka (2004) WDN – seismic hazard		AB, R	
Adachi and Ellingwood (2008) WDN – seismic hazard and interdependency with the electric power system			AB, AD (b), (c)
Vugrin et al. (2010) General framework for infrastructure systems	AB, AD, R (3)		
Ouyang et al. (2011, 2012) Power transmission grid – random hazards and hurricanes	AB, AD, R (3)		
Wang et al. (2011) Interdependent electric power and water system – random failures and deliberate attacks on the power system			AB (b), (d)
Yazdani and Jeffrey (2012) WDN – no evaluation of disruptive events			AB (b), (c)
Gay and Sinha (2012) WDN – any disruptive event		R	
Francis and Bekera (2014) General framework – applied to power distribution system against hurricanes	AB, AD, R (1), (2)		
Farahmandfar et al. (2015) WDN – seismic hazard			AB (a), (b), (c)

- AB: Absorptive capacity
- AD: Adaptive capacity
- R: Recovery capacity
- Numbers in parenthesis refer to the methods for measuring the loss of system performance
- Letters in parenthesis refer to the focus of vulnerability-based studies

2.1.2 Prior Research in the Analysis of Intermittent Water Supply Networks

The prior research in the analysis of water supply systems has focused more on continuous water supply systems. Less attention has been given to the analysis of water supply systems in the context of intermittent water supply (Ilaya-Ayza et al. 2017). Relevant studies in the analysis of the IWS *physical network* are summarized and discussed in this section.

The analysis of the physical piped network has been the scope of the majority of prior research that studied IWS systems. These studies analyze different aspects of piped networks that operate under an intermittent water supply mode. These aspects include the performance of the network in terms of pressure, flow rates, leakage rates, and/or supply satisfaction (Andey and Kelkar 2007; Gheisi and Naser 2015; Mohapatra et al. 2014; Soltanjalili et al. 2013). Another aspect is the impact of water intermittency (i.e., pressure fluctuation and pipes emptying and filling cycles) on the physical condition of the pipe network (Agathokleous and Christodoulou 2016; Christodoulou and Agathokleous 2012). In addition, some studies focused on modeling and analyzing the detailed process of pipe filling and emptying (Lieb et al. 2015; de Marchis et al. 2010).

Another part of the literature that is related to the IWS *piped network* focuses on the issue of supply equity. In some IWS systems, consumers who are close to the water source get their supply faster and for longer time periods with greater pressure than those who are distant from the water source. This problem of inequity of supply is manifest in large networks where the water entering the network could take several hours to reach distant consumers (Ameyaw et al. 2013). Ameyaw et al. (2013) developed a multi-objective model to measure and improve supply equity and minimize the cost of additional source tanks in IWS networks. Gottipati and Nanduri (2014) proposed an index for measuring the supply equity in IWS networks and studied the effect of various design factors on the equity index. These two studies analyze physical design modifications to the network in order to address inequity. On the other hand, Ilaya-Ayza et al. (2017) analyzed operational modifications, in the form of optimizing supply schedules, to improve the equity of water supply. Therefore, their work can be considered an example of the analysis of the coupling between the *piped network* and the network manager/operator (i.e., the utility).

These research efforts focus on analyzing IWS networks under normal operation conditions. To the knowledge of the author, no previous study has analyzed IWS networks from a resilience point of view where the network's performance is assessed against physical disruptions. The unique aspects of IWS networks (including household tanks, supply schedules, and supply inequity) are expected to produce a network resilience behavior that is different from that of CWS networks.

2.2 Resilience Quantification Framework for IWS Networks[3]

The framework developed in this study quantifies the resilience of IWS physical networks that are characterized by local household water storage. The framework focuses on larger IWS systems where the network is divided into zones with different supply schedules. The framework is generalizable in terms of the forms of household water storage, the strategies for water rationing/scheduling, and the types of disruptive events and their intensities. The framework components are shown in Figure 2.2, along with tools used for analyzing each component. The proposed framework assesses three resilience capacities: *absorptive*, *adaptive*, and *restorative* capacities.

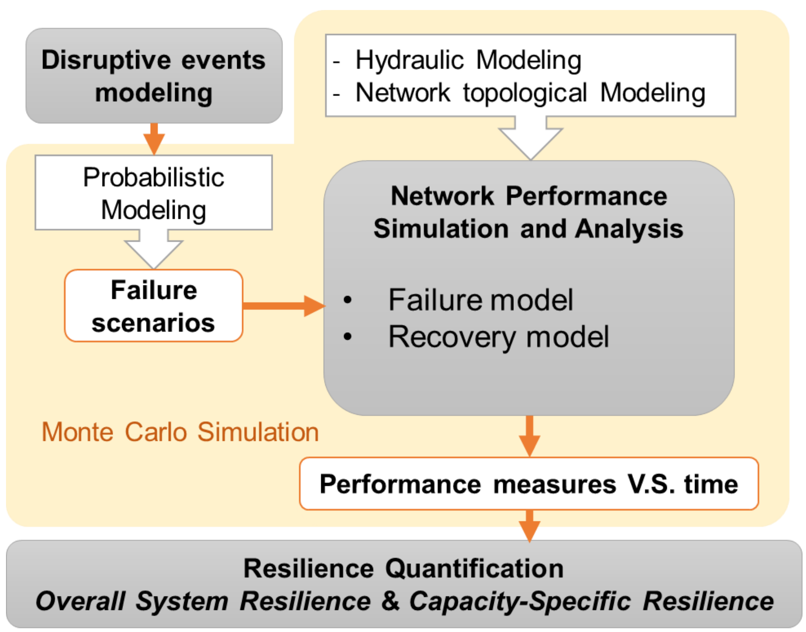


Figure 2.2. Framework Components and Modeling Tools

[3] Section adapted from Aljadhai and Abraham (2018)

2.2.1 Disruptive Events Modeling

The first component in this framework is the modeling of disruptive events that translates the occurrence of initial disruptive events into failure scenarios of the network components. The failure of network components is governed by vulnerabilities of components (the probability of failure given the intensity of the disruptive event). These vulnerabilities vary across different types of disruptive events, thus requiring different probability functions to be defined for each type of disruptive event. The output of this component is a matrix of failure scenarios where the failed network components are identified. Each failure scenario represents one realization (one set of draws) of the probability functions of different components vulnerabilities.

2.2.2 WDN Performance Simulation and Analysis

This component simulates the failure and recovery processes of the WDN. The simulation tracks specific hydraulic attributes of the network during the failure and recovery simulation. Although graph-theory based simulation has been widely used in the literature (e.g., Adachi and Ellingwood 2008; Wang et al. 2012; Yazdani and Jeffrey 2012) to simulate the performance of water distribution networks, it only provides an abstract representation of the flow in the network. On the other hand, hydraulic simulation provides an actual representation of the network performance by modeling the physical process of the water flow in the network. In addition, hydraulic simulation has the advantage of tracking the pressure in the network, which is crucial for determining the amount of water each consumer receives since the demand in many IWS systems is a function of the pressure (Ameyaw et al. 2013; Mohapatra et al. 2014).

2.2.3 IWS Network Performance Measures

Two main system measures are tracked for assessing the system's performance during disruptions: *serviceability index, SI* and *network-average tank filling ratio, ATFR*. Prior studies (Wang 2006; Shi and O'Rourke 2008) that focused on CWS networks defined the serviceability index (also known as demand satisfaction) as the ratio of total delivered demand to the total required demand for all demand nodes in the network. However, the concept of *demand satisfaction* is different in IWS networks since the supplied demand will not be evaluated only in terms of the volume of water delivered to the household, but also by considering the water available at the household storage. Hence, Serviceability Index, SI (taking a value between 0 and 1), is defined here as the ratio of the total volume of *accessible* water in households' storage (limited by the volume of household demand) to the total required demand for all households. *Serviceability Index, SI,* is calculated using Equation 2.1. Calculating the demand satisfaction for each household separately normalizes the household demands, which ignores the actual volume of the unsatisfied demand.

$$SI_t = \frac{\sum_{i=1}^{N}(Q_{access,t,i})}{\sum_{i=1}^{N}(Q_{req,i})} \tag{2.1}$$

Where SI_t is the system serviceability index at time t, ($0 \leq S_t \leq 1$), $Q_{req,t,i}$ is the required demand at household node i, and N is the number of household nodes in the network. $Q_{access,t,i}$ is the accessible water in the household storage (limited by the household demand at time t) at node i at time t, and it is determined using Equation 2.2. In other words, *SI* calculates how much of the required demand was satisfied by stored water in the household (takes a value between 0 and 1).

$$Q_{access,t,i} = \begin{cases} 0, & Q_{stored,t,i} \leq 0 \\ Q_{stored,t,i}, & 0 < Q_{stored,t,i} < Q_{req,i} \\ Q_{req,i}, & Q_{stored,t,i} \geq Q_{req,i} \end{cases} \tag{2.2}$$

Where $Q_{stored,t,i}$ is total volume of stored water in household i at time t.

ATFR is the network-average of the ratio of the volume of the stored water to the maximum volume capacity of water storage for all households in the network. In the case of uniform-shaped tanks (rectangular or circular), *ATFR* can be calculated as the ratio of the water depth in the household's tank (h_{w}) to the tank's depth (h_{t}) averaged across all tanks in the network, as shown in Equation 2.3.

$$AFTR = \frac{\sum_{i=1}^{N}\left(\frac{h_{\mathrm{w}}}{h_{\mathrm{t}}}\right)}{N} \tag{2.3}$$

The first performance measure, *SI*, assesses the network performance in terms of consumers' demand satisfaction and explains the performance of the network during the *damage propagation* and the *recovery* stages of the disruption-recovery cycle. However, during the *disaster prevention* stage, the system uses its absorptive capacity to withstand shocks and continue the normal operation with no service disruption. Performance measures that focus on the impact of the disruptions on the end users (such as *SI*, *proportion of surviving nodes*, or *proportion of nodes that meets a threshold*) fail to explain the system response at the prevention stage where there is no service disruption for the end users. Therefore, a performance measure that can examine the changes in water storage in the system could explain the absorptive capacity of the system that allowed the system to prevent a service disruption during the prevention stage. The *ATFR* represents the available water storage buffer in the system that helps the system to absorb the shocks and minimize the impact on consumers.

2.2.4 Resilience Metrics

Serviceability Index, SI, gives an overall indication of system performance in terms of the service received by the end users at the terminal nodes. When plotted across time, SI can explain the *combined effect* of the system's resilience capacities. On the other hand, *ATFR* is an indicator of the available *absorptive capacity* in the system (i.e., capacity of storage buffer). Using these two performance measures, two resilience quantities are proposed in this framework: *Overall System Resilience (OSR)* and *Capacity-Specific Resilience (CSR)*.

2.2.4.1 Overall System Resilience (OSR)

OSR captures the collective effect of all three resilience capacities, which is represented by the SI. OSR takes a value between zero and one and is calculated by comparing the area under the disrupted-system's SI curve to the area under the targeted performance curve. It is assumed that the targeted SI is always equal to one (i.e., all supply nodes have 100% demand satisfaction). Therefore, the targeted SI curve will be a straight line, as shown in Figure 2.3. OSR is calculated using Equation 2.4.

$$OSR = \frac{\int_{t_0}^{t_f} SI(t)dt}{(t_f - t_0)} \qquad (2.4)$$

Where t is time, t_0 the start time of the disruption, and t_f is the time where the system returned to normal operation.

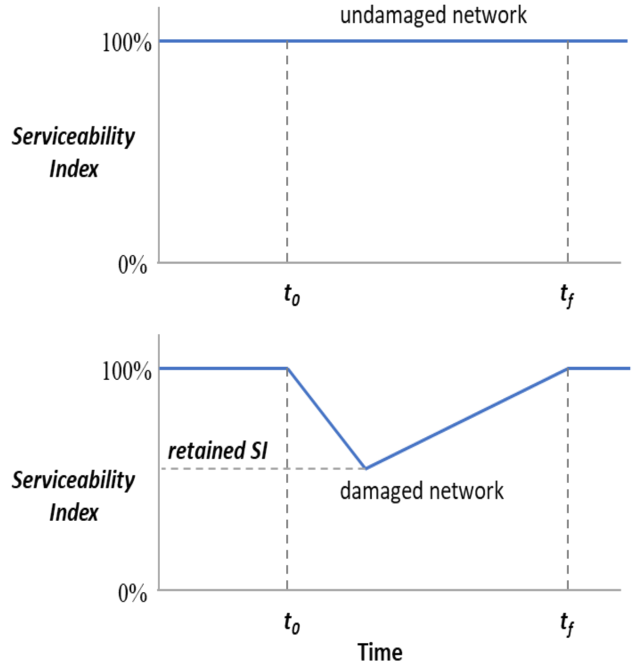


Figure 2.3. Illustration of Serviceability Index curves for undamaged and damaged networks

2.2.4.2 Capacity-Specific Resilience (CSR)

CSR represents a set of three resilience quantities for the three resilience capacities. CSR has a value between zero and one and is calculated for each resilience capacity separately. *Absorptive* capacity has two dimensions: the ability to withstand and prevent a disruption *and* the ability to minimize the consequences of the disruption. Absorptive CSR is calculated by a weighted sum of two parameters (Equation 2.5). The first parameter is the ratio of the area under the *ATFR* curve of the damaged network to the area under the *ATFR* curve of the undamaged network. This parameter captures the system's ability to withstand shocks and prevent disruptions. The second parameter is the performance retained post-disruption (shown in Figure 2.3). This parameter represents the system's ability to minimize the consequences of the disruption. The weight w in Equation 2.5 represents the importance of the retained SI to the system's analyzer in determining the system's absorptive resilience.

$$CSR_{Absorptive} = w\, SI_{retained} + (1-w)\ \frac{(\int_{t=0}^{t_f} ATFR_{damaged}\ dt\ )}{(\int_{t=0}^{t_f} ATFR_{undamaged}\ dt)} \tag{2.5}$$

Adaptive capacity is calculated by estimating the contribution of the adaptive measures in reducing the loss of OSR. The loss of OSR is calculated by comparing the OSR of a baseline scenario (without adaptive measures) to the OSR of the same scenario with adaptive measures, as shown in Equation 2.6. Adaptive measures (e.g., modifications to the operation of the network) are temporary recovery management actions that bring the system to an improved (intermediate) performance level during the disruption.

$$CSR_{Adaptive} = 1 - \frac{OSR_{without\ adaptive\ measures}}{OSR_{with\ adaptive\ measures}} \tag{2.6}$$

Restorative capacity can be assessed by the probability of the system to meet predefined recovery time and cost constraints when a probabilistic simulation is applied (Gay and Sinha 2012). In this framework, restorative capacity is defined as the probability of meeting pre-defined recovery time limits as shown in Equation 2.7.

$$CSR_{Restorative} = \frac{\sum(runs\ with\ recovery\ time \le recovery\ time\ target)}{number\ of\ runs} \tag{2.7}$$

CSRs explain the contribution of each resilience capacity on the overall resilience of the system, and hence, can guide the resilience enhancement decisions. However, there is an overlap between the effects of resilience capacities. For example, an enhanced absorptive capacity will have a positive impact on the restorative capacity of the system. Therefore, the OSR is used along with CSRs to account for the interdependencies between different resilience capacities.

2.2.5 Stochastic Simulation

There are several sources of uncertainties in quantifying the resilience of WDN. The main uncertainty is the one related to the initial failure of system components, which is characterized by the component's vulnerability. For natural hazards, *fragility curves* are used to specify the probabilities of reaching different failure states for network components giving the intensity of the hazard. Fragility curves are used for network components other than pipelines (tanks, treatment facilities, pumping stations, and wells). For pipelines, the probability of failure is estimated by calculating the *repair rate* (number of breaks per kilometer). Different fragility curves and repair rates have been developed in the literature for different types of natural hazards (earthquakes, floods, hurricanes, etc.). For initial failures caused by other disruptive events, probability distributions are often used to represent the vulnerabilities of components. Another source of uncertainty in the resilience quantification framework is the uncertainty in recovery durations for system components, which can also be characterized by probability functions.

To address these uncertainties, a *Monte Carlo* simulation is implemented in the resilience quantification framework. The Monte Carlo approach is best suited for simulation-based problems where a complex behavior of system parameters is present. In this framework, the limited number of uncertain parameters (including the initially failed network components and the recovery times) make the Monte Carlo simulation less complex, thus justifying its use for addressing uncertainties.

2.3 Evaluation and testing of the framework

The framework is implemented in the context of household-storage-based IWS networks. The simulation of the performance of the physical water network against disruptive events is developed in Python 3.6 environment. Figure 2.4 shows the simulation flowchart that describes the steps of the simulation of the water network failure and recovery, along with resilience calculations. Traditional hydraulic simulation software (such as EPANET, which was developed by the Environmental Protection Agency (EPA)) are designed to analyze water networks under normal operation conditions. Also, they have limited capabilities to manipulate the network parameters to analyze the network's resilience. This framework uses the Water Network Tool for Resilience (WNTR) to carry out the hydraulic simulation. WNTR is an open-source Python library that was developed by Sandia National Labs and the Environmental Protection Agency (EPA) (Klise et al. 2017). WNTR contains functions to add and remove network components, introduce damages to pipelines, modify network parameters, run hydraulic simulations, and carry out stochastic simulations. The usage of WNTR in this framework is shown in the simulation flowchart (Figure 2.4).

The recovery process for damaged pipes follows a method suggested by HAZUS-MD, a multi-hazard loss estimation methodology and software (FEMA 2015). This method prioritizes damaged pipes in a network, based on their diameters, and estimates the restoration times based on the productivity of restoration teams. This method requires specifying the number of available workers and assigns available teams to the repair of damaged pipes. When pipes are restored, the team(s) are reassigned to the restoration of other damaged pipes until all damaged pipes are restored.

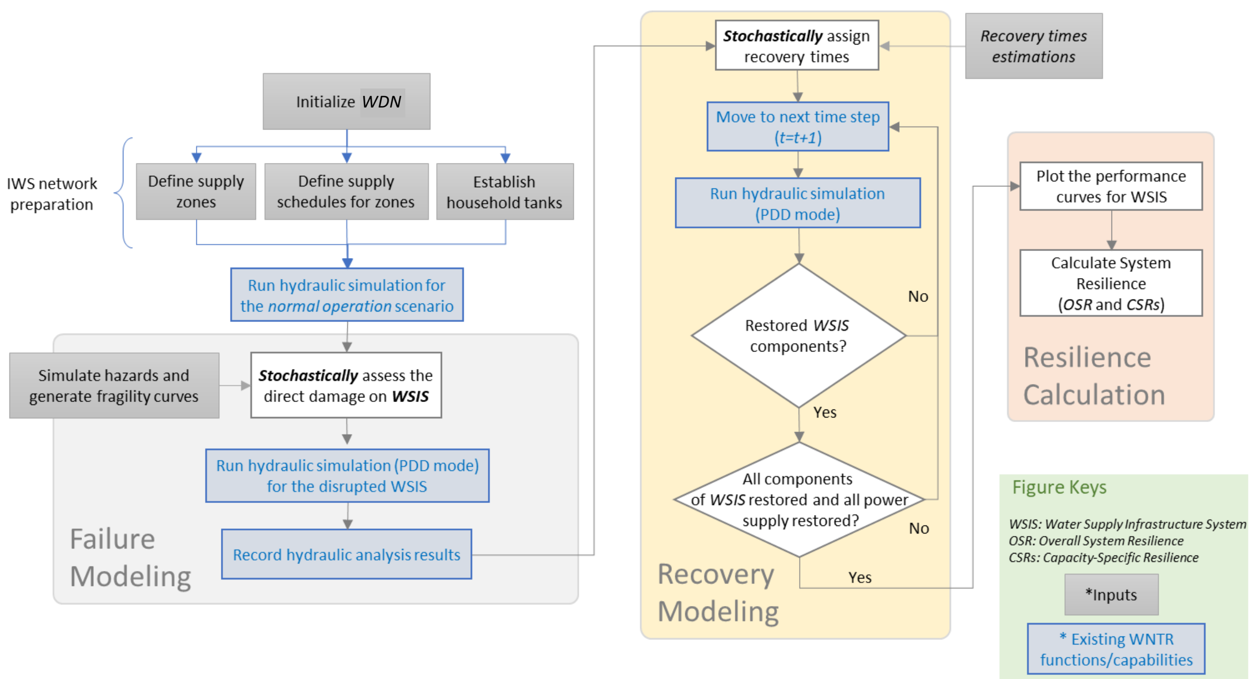


Figure 2.4 IWS Network Resilience Simulation Flowchart

2.3.1 Demand-Driven (DD) versus Pressure-Dependent-Demand (PDD) Simulation

Traditional hydraulic modeling software (such as EPANET) uses a demand-driven (DD) simulation approach where the demand for all consumers is assumed to be met, and then the pressure in the network is calculated accordingly. This assumption does not hold in damaged or pressure-deficient networks (even in CWS networks) where the demand supplied to consumers is a function of the pressure at their ends. Pathirana (2011) and Abdy Sayyed et al. (2015) proposed quasi-PDD methods by modifying the DD simulation in EPANET to model damaged networks. However, assessing the resilience of WDNs requires constant modifications to the network characteristics (adding and removing components) requiring flexibility and computational efficiency to carry out stochastic simulations that are not provided by quasi-PDD methods. On the other hand, WNTR introduced its stand-alone PDD simulation engine that solves the set of non-linear equations (Equation 2.8) to calculate the delivered demand at consumer nodes.

$$d = \begin{cases} 0 & p \leq P_0 \\ D_f\left(\frac{p-P_0}{P_f-P_0}\right)^{\frac{1}{2}} & P_0 \leq p \leq P_f \\ D^f & p \geq P_f \end{cases} \tag{2.8}$$

Where d is the actual demand (m³/s), D_f is the desired demand (m³/s), p is the pressure (Pa), P_f is the pressure above which the consumer should receive the desired demand (Pa), and P_0 is the pressure below which the consumer cannot receive any water (Pa).

2.3.2 IWS Modeling

The hydraulic simulation of IWS networks requires some special considerations to address unique aspects of IWS networks. These aspects are, namely, household storage, special demand patterns, and supply cycles. The following sections explain each aspect and show how it is considered in the hydraulic simulation.

Modeling Household Storage

In many IWS systems, consumers have long adapted to the supply intermittency by storing water at their households during supply times. Household storage can be in different forms ranging from constructed or installed tanks to simple containers. The way the water is extracted from the network (i.e., rate, duration, and quantities) varies accordingly. In this framework, the IWS network is characterized by underground household tanks that are operated using floating valves. Since the function of underground household tanks in the hydraulic model is limited to receiving water with no backflow to the network, they are modeled as artificial reservoirs connected to the demand nodes (Mohapatra et al. 2014). Reservoirs are hydraulic model components used primarily as the water source in the network, but they can be used as water bodies for network discharge. A check valve is added to the pipe connected to the artificial reservoir to prevent water backflow to the network. WNTR have the capability of pausing and resuming the simulation, which allows the tracking and recording of water levels in household tanks outside the hydraulic model (by tracking the inflow to the artificial reservoirs), which makes the hydraulic simulation faster.

Special Demand Simulation

In contrast to demand patterns in CWS networks that are distributed over time with little fluctuations, the hydraulic demand in IWS networks does not follow a smooth demand pattern, and it is characterized by peaks in demand over shorter periods of time since households try to store as much water as they can during the supply time. In the context of this framework demonstration, the water from the network is fed directly to the household's underground tank until the tank is full, then the water is shut-off using a floating valve. As a result of having many household underground tanks in the network, the water discharge at the household's tank is a function of the water pressure at that node in the network. This feature of IWS networks stresses the importance of using a pressure-dependent demand (PDD) simulation not only for the damaged network (as previously discussed for CWS networks) but also during the simulation of the normal operation of the IWS network.

Modeling Supply Cycles

In larger IWS networks, the network is often divided into sectors (also called district metered zones, DMZs) and different supply schedules are assigned to those zones (Ilaya-Ayza et al. 2017). To model this feature of IWS systems, the cycles of opening/closing the control valves that control the water flow for these zones are implemented in the hydraulic simulation by constantly checking the supply schedules.

Figure 2.5 illustrates the method for incorporating these aspects of IWS networks in the hydraulic simulation. At each time step, the supply schedule is checked to update the status of the isolation links (i.e., open or closed) for each DMZ. The hydraulic simulation then solves the hydraulic equations to calculate the pressure-dependent inflow for the artificial reservoirs (i.e., household tanks). A separate matrix (Household Tanks matrix), which contains the water level for each household tank at each time step, is updated by adding the inflow for the artificial reservoir to the tank's previous water level. To simulate water withdrawal from household tanks, the water levels in tanks are updated by subtracting the actual water demand for the household. Finally, the household tanks that are completely filled are shut-off and isolated, preparing the network for the simulation of the next time step. This process is repeated for each time step until the end of the simulation duration.

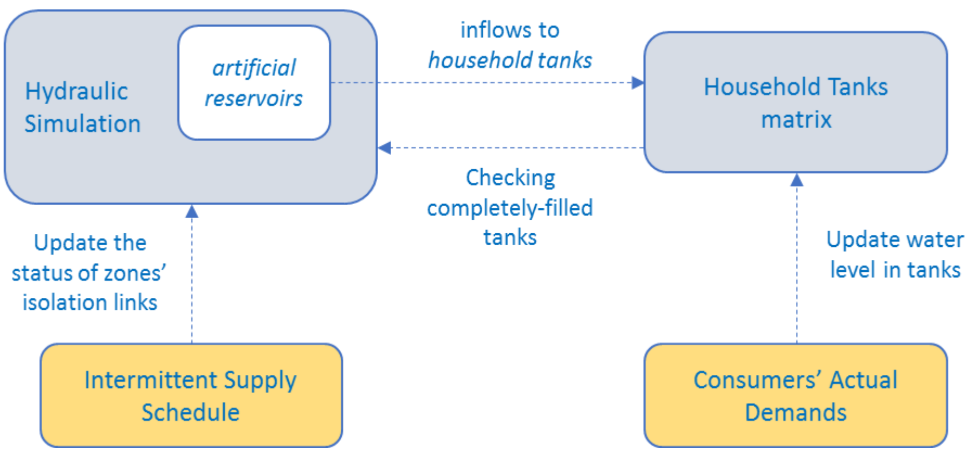


Figure 2.5. Modeling the Aspects of IWS Networks in the Hydraulic Simulation

2.3.3 Case Study

The framework is evaluated using a case study of a subnetwork from the water supply network in a city in the Middle East (described earlier in Section 1.8). Figure 2.6 illustrates the typical household water system in the city where consumers rely on underground (or on-ground) storage tanks that are operated using floating valves and an electrical pump to elevate the water to a roof-top tank, and the water then runs through the house by gravity. Only the underground tank is included in the hydraulic analysis since the other components of the household system have no effect on the hydraulics of the water network.

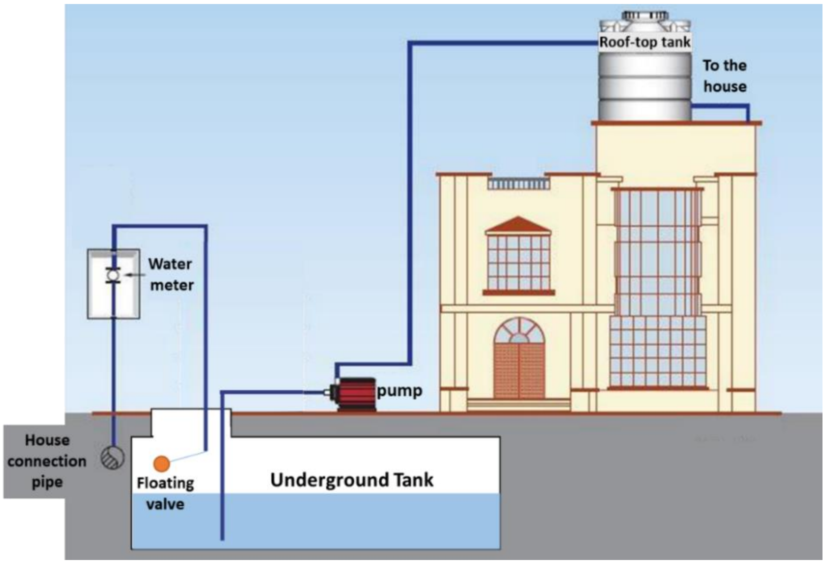


Figure 2.6. Typical household water system in case study city

The water network in the case study city runs mainly on gravity due to a 90-meter elevation difference between the city and the main network source tanks. Booster pumping stations exist in some low-pressure areas in the network. The chosen subnetwork was suggested by the water utility as a representative subset of the whole network in terms of network configuration, elevations, pressure, and household storage capacities.

Data Processing

The sub-network is connected to the city's network through two water mains (300 millimeters in diameter). Two reservoirs were added in the hydraulic model to represent these two sources with appropriate water heads that reflect the actual water pressure in the network during normal operation. The evaluated network consists of 1068 junctions (out of which 605 are demand junctions), 1258 pipes, and two sources reservoirs. Each demand junction represents 3-5 houses. A network skeletonization process provided by WNTR was applied to abstract the network structure while preserving its operational characteristics (Figure 2.7). The number of pipes and junctions in the original network was reduced by around 40%. The skeletonized network consists of 384 demand junctions, where each junction represents 6-10 houses. Figure 2.8 shows the actual demand for the nodes in the skeletonized network (i.e., aggregated demand for households sharing the node). To include household underground tanks in the hydraulic model, each demand junction was connected to an artificial reservoir with a dummy junction and a check valve to prevent backflow from the household tank (i.e., artificial reservoir) to the network as shown in Figure 2.9. The demand of the original node (that represents the households) is set to zero.

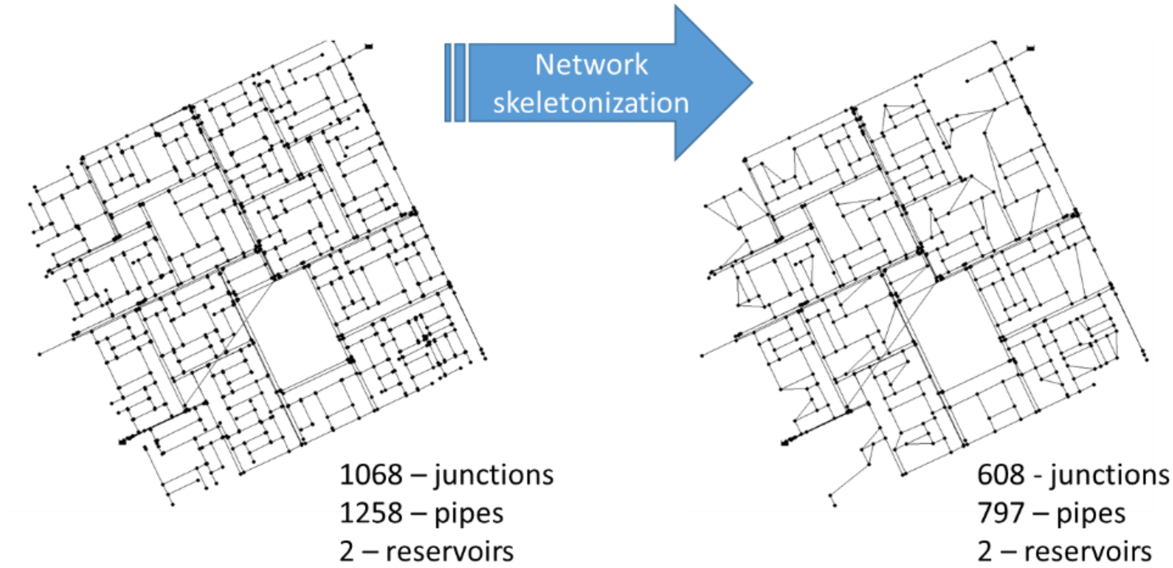


Figure 2.7. Network Skeletonization Results (left: original network, right: skeletonized network)

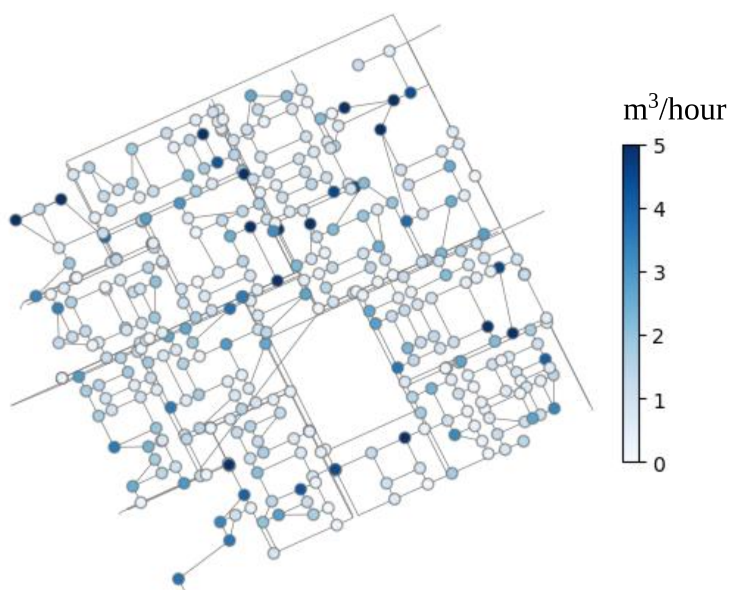


Figure 2.8. Demand for nodes in the skeletonized network

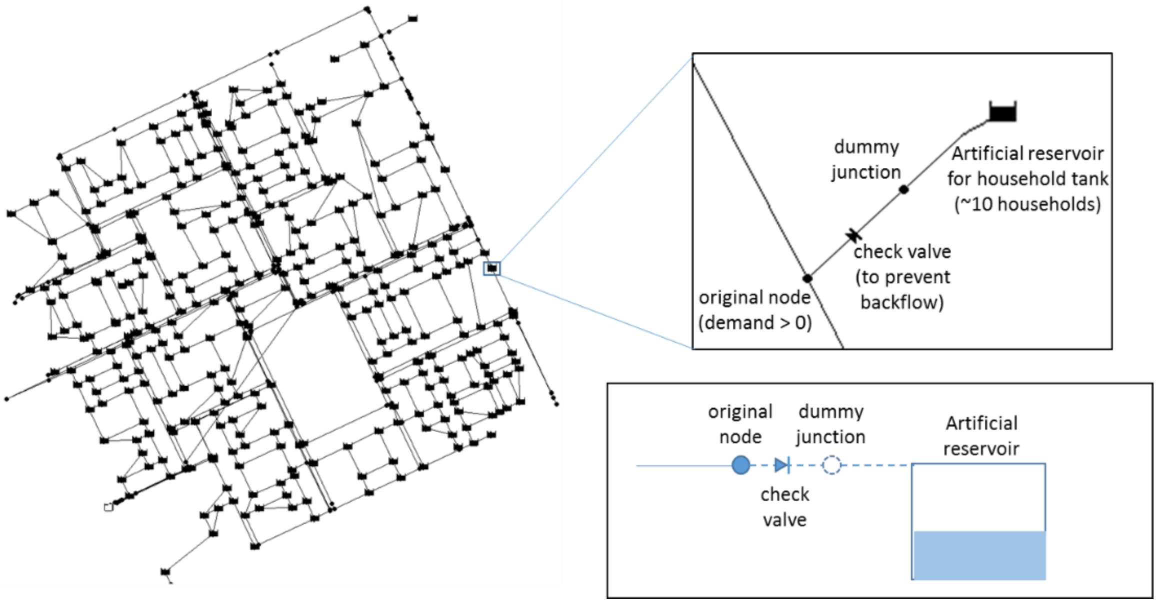


Figure 2.9. Modeling household tanks as artificial reservoirs

Within the chosen network, four DMZs were established, representing four isolatable zones (Figure 2.10). The pipes that control the flow to each zone were identified using topological processing that identifies the links that isolate the zone.

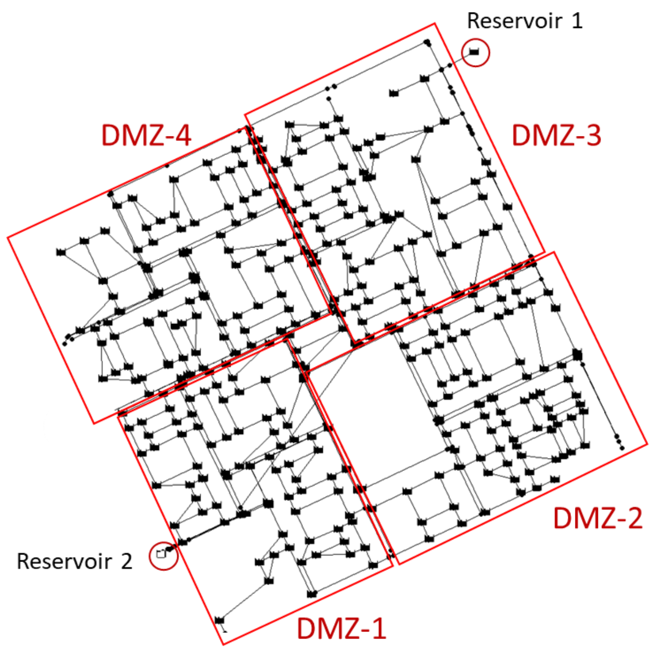


Figure 2.10. Demand Metered Zones (DMZs) and the network's two water sources

Analysis Setup

The capacity of household storage tanks is not included in the acquired network data. However, it was assumed that tank sizes correspond to the households' demands. Therefore, tank storage capacity (SC) is expressed in terms of the number of days it can supply the household demand. For example, if the household demand is 2 m^3/day and the tank volume is 20 m^3, the storage capacity will be 10 days. In order to isolate the effect of the variability of storage capacity among households, all tanks in the network were given equal capacities (in terms of days of supply), while having different volumes that correspond to the households' demands. By using this measure of storage capacity, the effects on the network performance will be limited to other variables of interest (e.g., damage intensity, recovery efforts, and the timing of the disruption).

In terms of the operation of the network, a representative supply schedule was established (Figure 2.11) to represent a typical household supply in the city (i.e., typical pressure and time required to fill tanks). The supply schedule is based on a 2-day supply duration for each zone. Under this supply schedule, the network always operates with 100% satisfaction for all consumers under normal operating conditions. Figure 2.12 is a visualization of the process of filling tanks in the network for one cycle (showing the tank filling ratio at the end of each day) following the supply schedule and starting with empty tanks with a storage capacity of 5 days.

Zone	Day1	Day2	Day3	Day4	Day5	Day6	Day7
DMZ-1	■	■					
DMZ-2			■	■			
DMZ-3				■	■		
DMZ-4						■	■

Figure 2.11. The weekly supply schedule

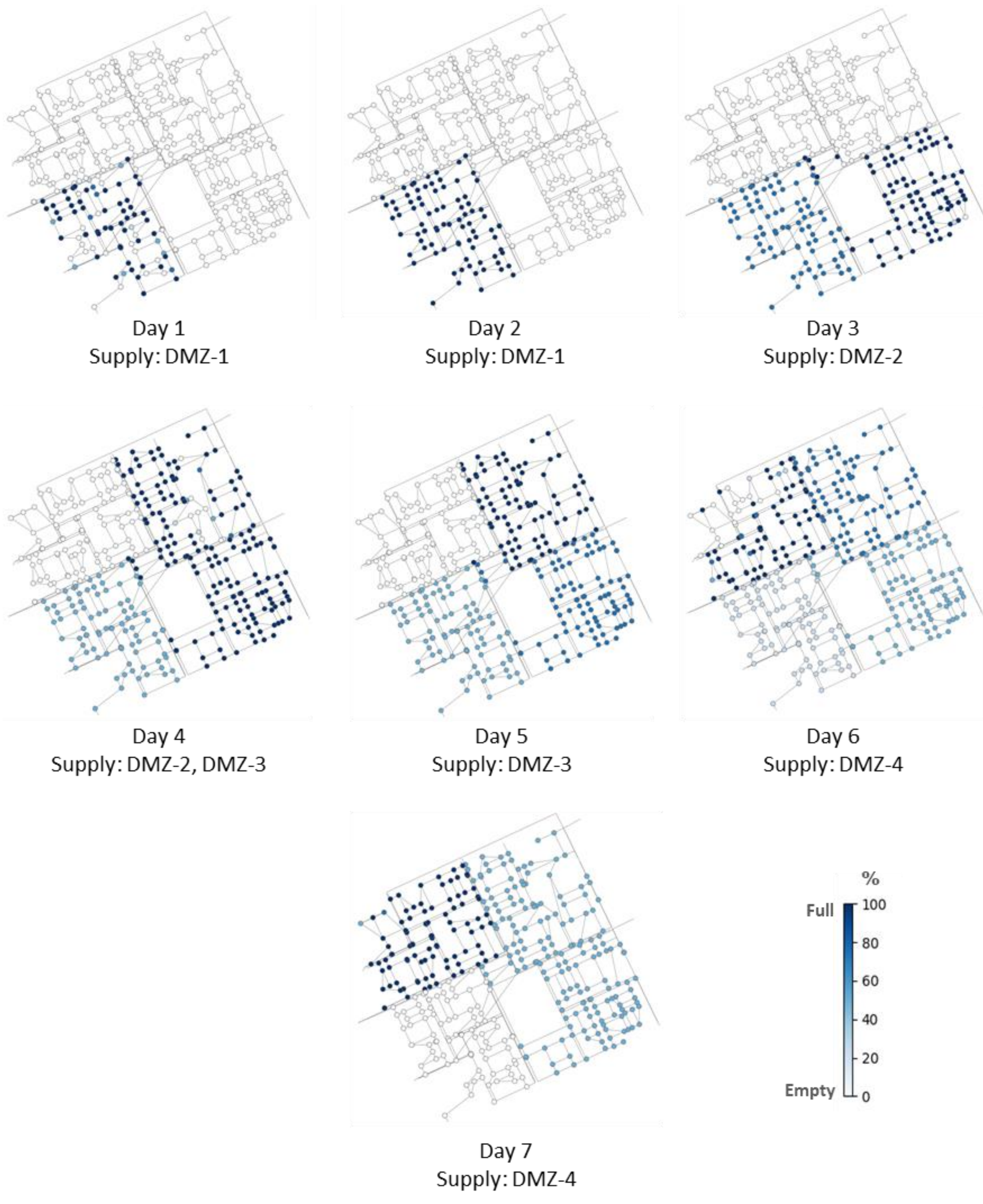


Figure 2.12. Example of tank filling ratio over time during normal operation (5-day storage capacity)

2.3.3.1 *Analysis of the network under normal operation conditions*

Using the weekly supply schedule in Figure 2.11, a set of baseline scenarios for the performance of the IWS network under normal operation conditions are analyzed. The normal operation of the network means that all consumers' demands are satisfied by the network at all times. Storage capacities are set to be greater than or equal to 6 days to ensure a 100% demand satisfaction. These baseline scenarios (for different storage capacities) are used later to evaluate the resilience of the network during disruptions. Figure 2.13 shows an example of the simulation results for 8 days of storage capacity (for all tanks in the network). The results include the performance curves for the serviceability index (SI) and the network-average of tanks filling ratios for the simulation of three weeks. Different coloring shades are used to denote the duration of the supply of the zones following the supply schedule (an overlap exists between the supply durations for DMZ-2 and DMZ-3). The SI remains at 100% throughout the simulation, where consumers' actual demand is always satisfied. The average tank filling ratio (AFTR) starts with a value of one since household tanks were set to be completely full at the beginning of the simulation. However, given the intermittent supply to households, household tanks will not be completely full. Hence, the average of the ratio of tank filling declines until it reaches a steady-state pattern after one cycle of the supply schedule (i.e., one week).

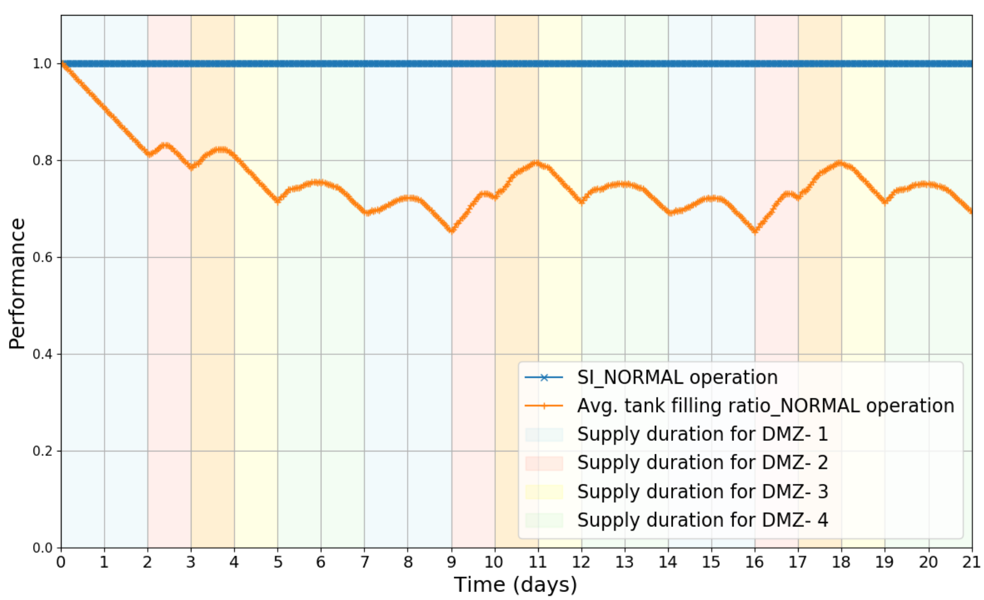


Figure 2.13. Sample results of the performance (SI and AFTR) of the IWS network for three weeks of normal operation for 8-day storage capacity

Table 2.2 summarizes the attributes of the zones during normal operation. These attributes show the variability in the water supply to different *zones* in the network. For example, DMZ-2 and DMZ-3 have hydraulic and topological attributes (i.e., the number and size of the zone's inlet pipes and pressure at the inlets) that resulted in greater inflow rates to the zones. The hydraulic attributes of zones depend on the topology of the network and the zone's connectivity to the water sources. These attributes help in explaining the variation in the performance of different zones both during normal operation and during disruptions, as discussed in the following sections.

Table 2.2. Attributes of Demand Metered Zones (DMZs) during normal operation

Zone	**Number of household tanks**	**Elevation (m)**		**Number of inlet pipes**	**Average diameter of inlet pipes (m)**	**Avg. pressure head at inlets (m)**	**Total inflow rate* (m^3/s)**
		Mean	**Std.**				
DMZ-1	84	620.2	1.85	4	0.16	13.53	0.13
DMZ-2	91	620.2	1.63	6	0.143	12.69	0.61
DMZ-3	83	620.6	1.30	6	0.16	15.18	0.59
DMZ-4	92	620.4	1.74	5	0.188	10.34	0.29

* During normal operation

2.3.3.2 Analysis of Supply Inequity

Supply inequity is one of the common issues reported in IWS networks with household water storage. Household tanks that are far from the source obtain water at a lower pressure (or do not get water at all) until the tanks that are closer to the source get filled and are shut off. As a result, there is a variation in the time at which tanks get completely filled, resulting in the inequitable distribution of the water, especially if the supply duration is not sufficient. Supply inequity is a result of the variability of supply at two levels: the network level and the zone level. Figure 2.14 shows the probability distribution of the time required to completely fill tanks in each of the four zones in the analyzed network (given a 7-day storage capacity as an example). These zone-wise curves are generated for each zone separately, starting with empty tanks and assuming supply to the zone until all tanks in the zone are completely filled while isolating other zones. As shown in Figure 2.14, tank filling times follow a normal distribution. For a given tank size (7 days in Figure 2.14), the difference in the means of the normal distribution curves represents the variability in supply among network zones. This network-level variability is attributed to the location of the zone within the network (i.e., the pressure at the zone inlets) and its connectivity to the network (i.e., number and size of the inlet pipes), resulting in different inflow rates to the zone. For this example, household tanks in DMZ-2 get full at a faster rate compared to the other zones reflecting the higher total inflow to DMZ-2, as shown in Table 2.2. On the other hand, the standard deviations of the normal distributions represent the variability in supply between households within each zone. This zone-level variability is attributed to the layout of the zone (i.e., the connectivity among nodes within the zone). The results show that both variabilities (i.e., among zones and within the zone) are important to describe the supply pattern for individual households. For example, although DMZ-4 has a faster rate of filling tanks than DMZ-1 (i.e., a lower mean value), it has a more spread curve (i.e., a higher value of standard deviation), which causes a longer time required to fill *all* tanks in DMZ-4.

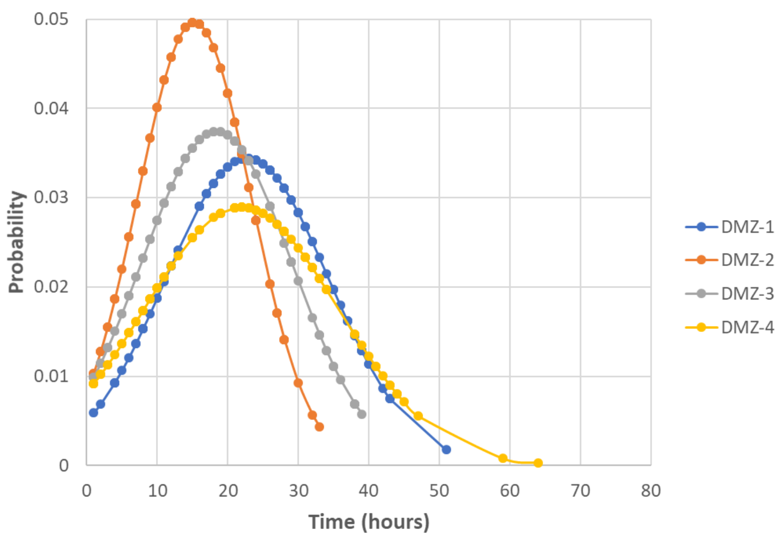


Figure 2.14. Sample of probability distributions of the time required to completely fill tanks following a zone-wise unlimited supply (storage capacity= 7 days)

To analyze the effect of varying the storage capacity on supply inequity, Figure 2.15 shows the distribution of the time required to completely fill tanks in each zone at different storage capacities. As shown in Figure 2.15, the average time required to completely fill the tanks increases as the storage capacity increases, which is a direct effect of longer times required to fill individual larger tanks. In addition, the standard deviation also increases with the increase in tank sizes, which reinforces the supply inequity within the zone since larger tanks cause a further delay of supply to the tanks that are far from the zone sources.

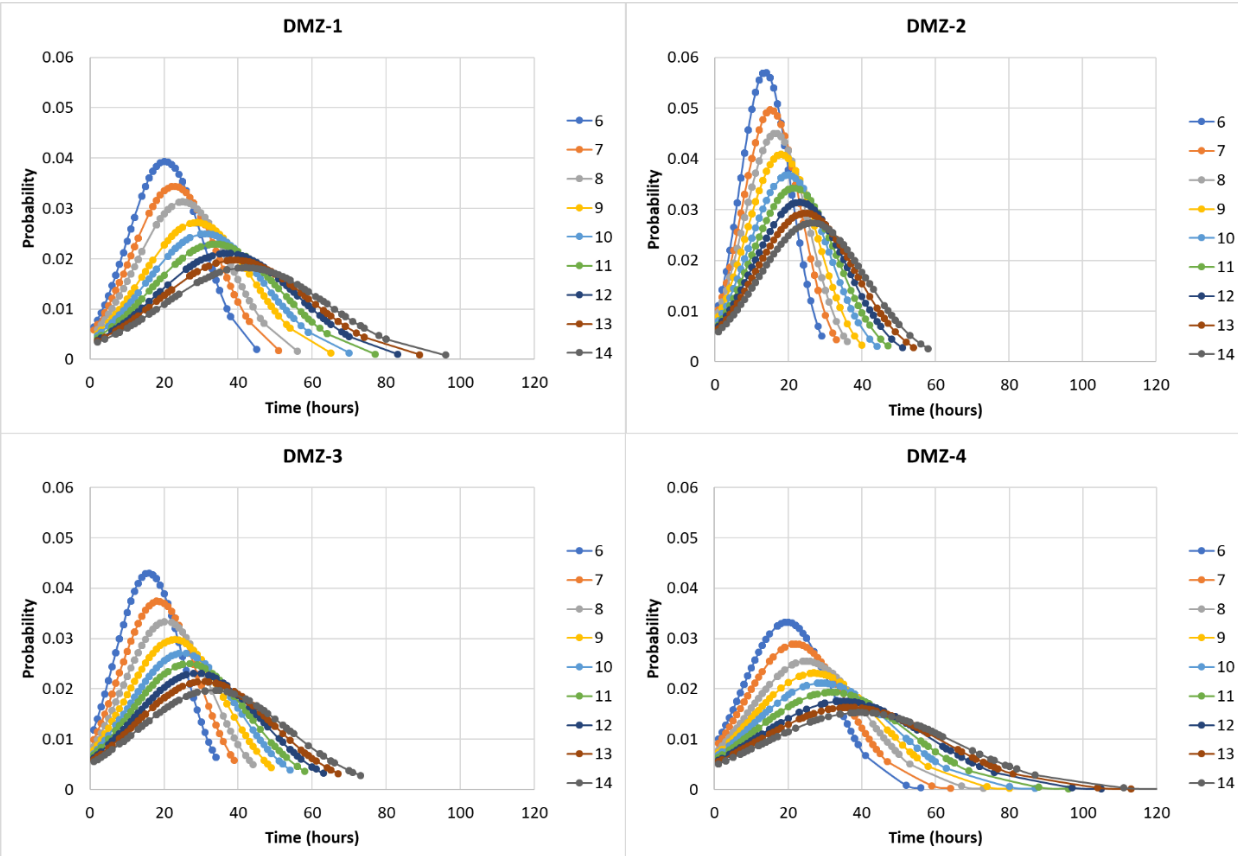
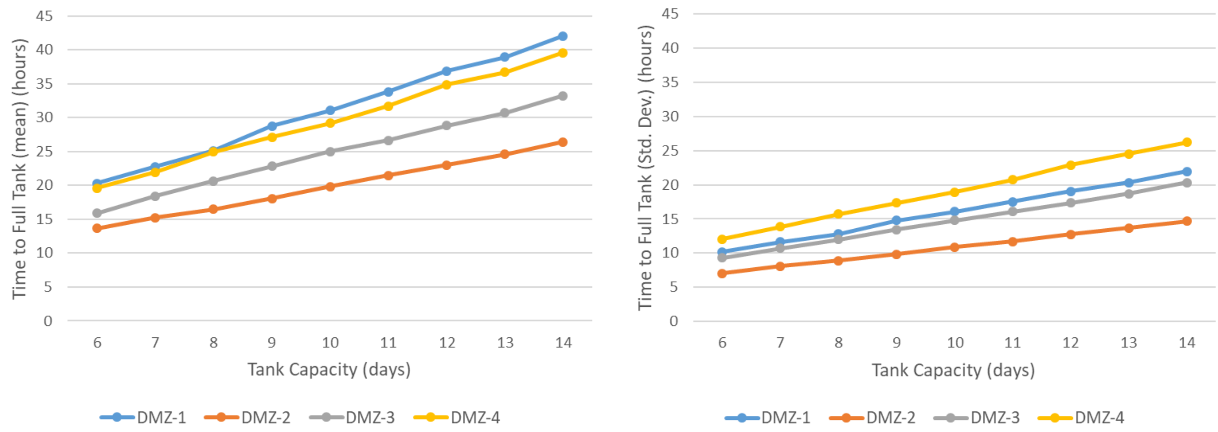


Figure 2.15. Effect of varying the storage capacity on the probability distributions of the time required to completely fill individual tanks for each zone

Figure 2.16 shows the increase in the mean and the standard deviation of the time required to completely fill individual tanks in each zone. Both the mean and the standard deviation increase in a linear fashion with the increase of storage capacity, which shows that the underlying interdependency relationship between households' tanks does not change with the increase in storage capacity as long the variation in tank sizes is fixed. This finding suggests that the zone-level supply inequity can be described by the zone's topology and the variation in the sizes of household tanks.

The results of this analysis show that although supply is divided between zones based on time scheduling, the supply is divided between households within the zone in a rather sequential basis (where tanks start filling when other tanks are full). This behavior is a result of the demand pattern of households withdrawing water from the network for storage purposes.



(a) (b)

Figure 2.16. Effect of tank size on (a) the mean of the time to completely fill individual tanks, and (b) the standard deviation of the time to completely fill individual tanks

2.3.3.3 Analysis of Disruption Scenarios

In order to evaluate the resilience of the IWS network, two scenarios of disruptions are identified: *pipe-damage disruptions* and *source disruptions*. These two scenarios differ in terms of the intensity of the disruption (i.e., partial vs. whole-network impact), and represent two different sets of disruptive events.

Scenario 1: Pipe-Damage Disruption

Pipe-damage disruptions represent internal physical disruptive events that result in damaging some pipes in the network. Such disruptive events include natural events (e.g., earthquakes, flooding, flash floods), deliberate attacks, and random failures that may damage some pipes in the network. The pipe-damage disruption can also represent planned/anticipated disruptions to the network (e.g., pipelines maintenance, inspection or replacement). In this analysis, a stochastic pipe-damage scenario is used where 10% of the critical pipes in the network (i.e., those greater than 300 mm in diameter) are assumed to fail in a random manner. Figure 2.17 shows these critical pipes that connect the zones to the water sources in the network.

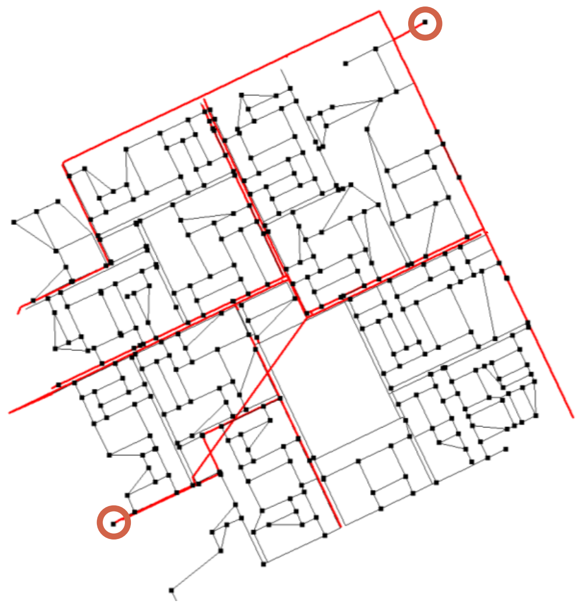


Figure 2.17. Critical pipes in the network (> 300 mm in diameter)

Scenario 2: Source Disruption

While the pipe-damage scenario affects the network partially, disruptions at sources represent disruptive events that occur externally and impact the whole network. Source disruptions are considered to evaluate the response of the network to wide-spread, longer disruptions. Source disruptions can represent any disruptive event (natural event, deliberate attack, or random failure) that affects the operation of the water sources (e.g., water reservoir and/or treatment plant), and that results in a partial or full shutoff of the water supply. In this case study, the scenario of source disruptions represents the impact of disruptions of other parts of the city's whole network that affect the supply to the subnetwork under study. Source disruptions are assumed to completely disable the two water sources in the subnetwork.

Scenarios Combinations

The resilience of the IWS network depends on both the attributes of the network (e.g., structure, household storage characteristics, and supply scheduling) and the attributes of the disruption (e.g., timing of occurrence, intensity, and duration). Table 2.3 gives a brief description of the variables that affect the resilience of the IWS network.

Table 2.3 Description of the variables that determine the resilience of the IWS network

Variable	**Description**
Household Storage Capacity (SC)	The capacity of household water storage expressed as the number of days it can supply the household's demand
Recovery Duration (RD)	The time required for completing all restoration efforts of damaged network components
Supply Inequity	The variation in tanks filling within a zone (i.e., the standard deviation of the time required to completely fill an individual tank in the zone)
Supply Scheduling and Supply Durations (SS)	The original scheduling of supply between zones

For this part of the analysis, the supply schedule is set to be static throughout the analysis, assuming that the water utility does not change the supply schedule during the disruption and that the utility's response is limited to restoring the failed network components.

Figure 2.18 shows the different combinations of the network and the disruption variables. Each of the two disruption scenarios can have different combinations of *household storage capacity*, *timing of the disruption (with respect to the supply schedule)*, and *recovery duration/speed*. In this case study, household storage capacity is expressed in terms of the number of supply days, as explained earlier.

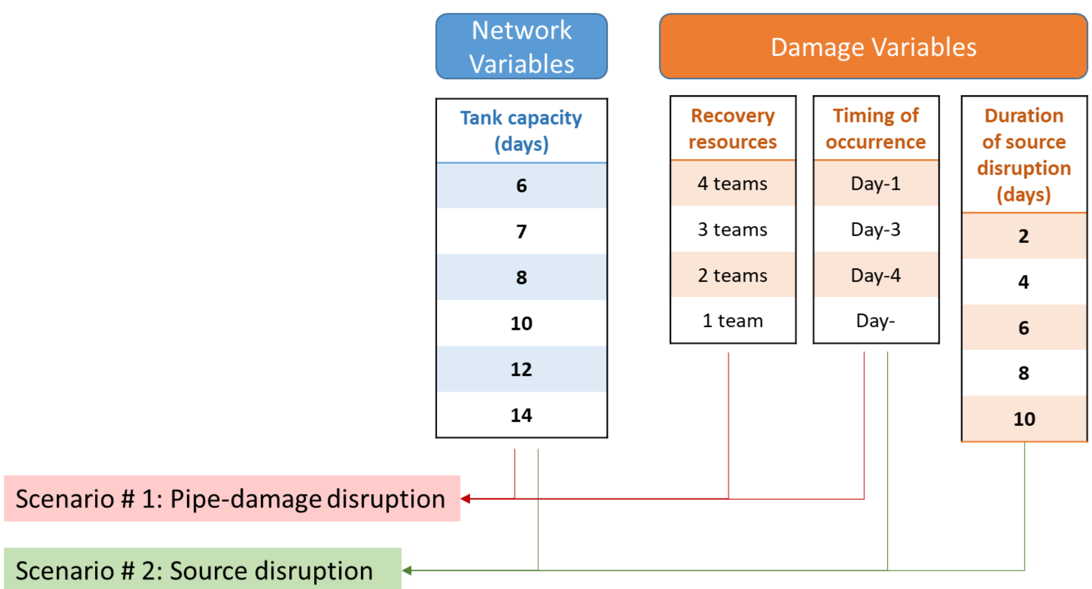


Figure 2.18. Scenario combinations

In IWS networks, the timing of the occurrence of the disruption (with respect to the supply schedule) has an effect on the network resilience because of the variation in the response of different zones to the disruption (due to the zone's hydraulic performance and *supply inequity*). If the disruption is extended beyond the length of the supply schedule (i.e., one week), the timing of the disruption will have less effect on the network's response since the disruption will affect all zones. For each zone in the network, the worst timing of the disruption would be the time where the zone has the lowest volume of stored water in household tanks (i.e., at the beginning of the supply to the zone). In this analysis, the four worst-case timings of the disruption are identified, which corresponds to the timings of the beginning of the supply to each zone (i.e., beginning of Day 1, Day 3, Day 4, and Day 6).

The recovery duration is the time required to restore the water supply to the network. The length of the recovery depends on the recovery process and strategy (i.e., priority and resources). For the pipe-damage scenario, a modified version of the recovery method suggested by HAZUS (software developed for FEMA) is used where recovery teams are assigned to damaged pipes based on priorities established based on pipe size. The variation of the recovery length is expressed in terms of the available recovery resources (four scenarios of the number of recovery teams are used). Therefore, the uncertainty in the recovery duration depends on the uncertainty of the pipes that failed. For the source disruption scenario, deterministic scenarios of the recovery length for restoring the water supply are assumed to represent the recovery of any component(s) outside the analyzed subnetwork.

2.3.3.4 Results Generation and Sample Results

A total of 96 stochastic combinations of the pipe-damage scenario were simulated using a Monte-Carlo simulation of 100 runs for each combination to address the uncertainty in the initially damaged pipes. It was observed that the mean value of OSR reaches a steady-state (change in the mean is less than 0.001) after around 50 runs. For the source disruption scenario, a total of 120 deterministic combinations were simulated. A sample of the results of one simulation combination for each scenario is presented here to illustrate the results of the two performance measures (*SI* and *AFTR*) and to explain their interpretations.

A sample of one simulation combination for the pipe-damage disruption (10-day storage capacity, disruption occurs at the beginning of Day 6 of the supply schedule, and 3 recovery teams) is presented in Figure 2.19. The top part of Figure 2.19 shows the mean, the 75^{th}-25^{th} percentiles, and the 90^{th}-10^{th} percentiles for the performance profile of the network's serviceability index (SI) for the 100 simulation runs. The bottom part of the figure shows the profile for the network-average tank filling ratio (AFTR) for the 100 simulation runs. Network disruptions are always introduced during the second supply cycle (i.e., second week) to ensure a normal steady-state performance condition when the disruption is introduced. The results of the SI show a delay in the network response to the disruption due to the available storage buffer in household tanks in the affected zones. For this example, the disruption occured at the time where DMZ-4's supply began (the beginning of day 6 in the supply schedule). Most households in DMZ-4 had a 5-day supply available in their tanks when the disruption occurred. Therefore, the network's SI remained at 100% until around 104 hours after the disruption when household tanks in DMZ-4 started to run out of water, since they missed the supply during this cycle. The network performance (i.e., SI) drops to an average of 85% five days after the disruption (the beginning of day 17 in the figure). Although the pipe recovery (on average) was completed three days after the disruption (end of day 14 in the figure), the network's SI has not improved until the supply was resumed to DMZ-4 in the following cycle. The SI curve also shows that the network performance dropped again during the following supply cycle (after the end of supply duration to DMZ-4, end of day 20 in the figure) since the supply duration for the zone (i.e., 2 days) was not sufficient to fill all tanks in the network due to the greater supply inequity associated with greater storage capacities (i.e., 10-day capacity). The SI performance went back to 100% when the supply was resumed to DMZ-4 on day 26. In this example, the disruption affected only one zone (DMZ-4), given the combination of storage capacity, recovery speed, and timing of the disruption. However, for other combinations, the disruption impact can extend to more than one zone, causing a greater drop in the SI curve.

The curves of the network-average tank filling ratio, *AFTR*, (the bottom part of Figure 2.19) shows the drop in network's storage buffer following the disruption, compared to the network's storage buffer during normal operation. Starting from the time of the disruption (day 12 in the figure), households in DMZ-4 start to use the storage buffer in their tanks, causing the network-average buffer to decline. As the recovery of damage pipes progresses, the average tank filling ratio converges to the original normal operation profile (reaches normal operation at day 28). Different scenario runs (with different damaged pipes) result in a variation in the network's response in terms of the drop and the recovery of the network's average household storage.

Figure 2.20 shows the result for one deterministic simulation of one combination of the source disruption scenario (10-day storage capacity, 6-day recovery duration, and disruption occurs at the beginning of Day 6 of the supply schedule). The SI results show a similar delay in the effect of the disruption on the network performance due to the available water storage. The longer (6-day) recovery duration caused a complete shut-off for the supply for DMZ-4, DMZ-1, and DMZ-2. The drops in the SI values on days 17, 19, and 21 in the figure represent the tanks running out of stored water in these zones, respectively. The SI curve also shows the post (secondary) disruption that occurs during day 31 as some tanks in DMZ-4 and DMZ-1 did not have enough time to sufficiently fill during the previous supply cycle given the issue of supply inequity. The tank filling curve (bottom of Figure 2.20) that tracks the changes in the value of ATFR helps in explaining the network's SI performance. The negative slope of the ATFR curve indicates the shut-off of the supply to the network, while the positive slope indicates a normal supply (that follows the supply schedule).

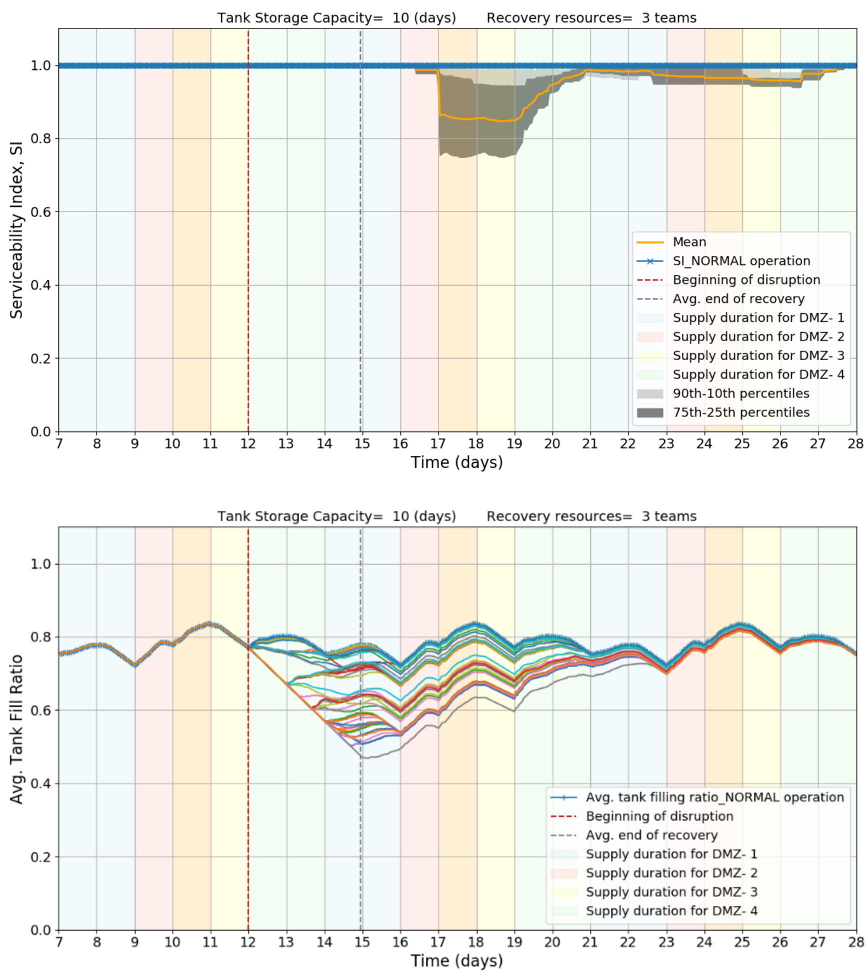


Figure 2.19. Sample results (for 100 runs) for one combination of the pipe-damage disruption (SC= 10 days, Recovery resources= 3 teams, and disruption timing= Day 6)

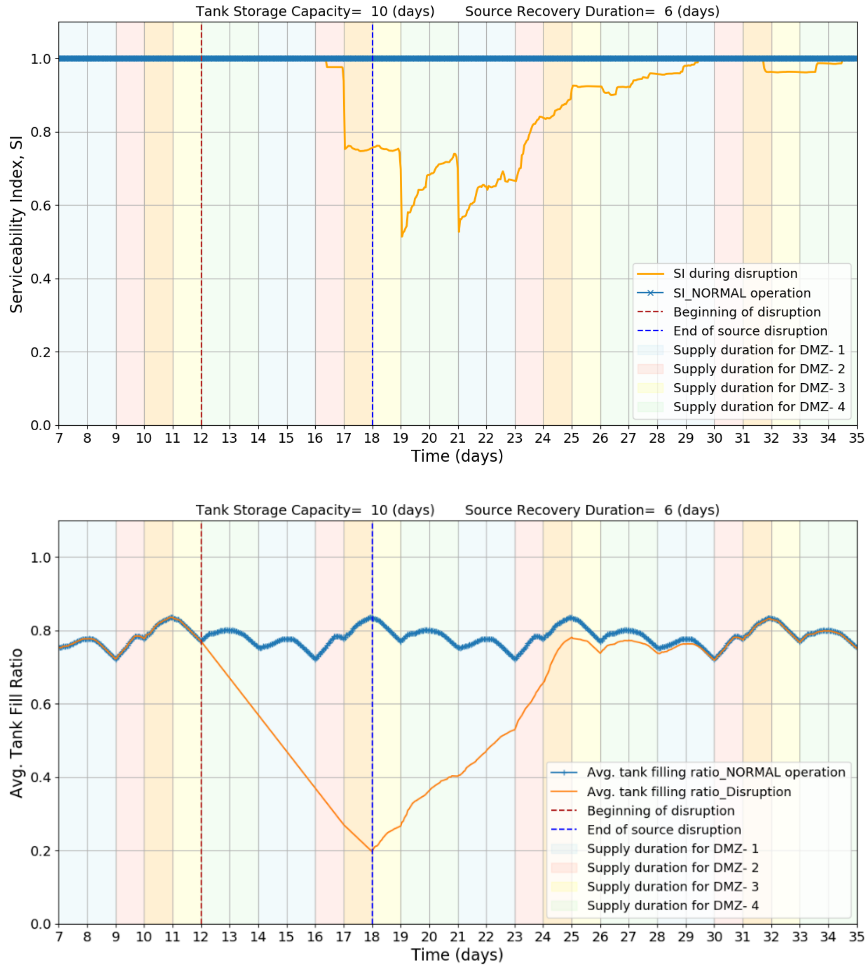


Figure 2.20. Sample results for one deterministic combination of the source disruption (SC= 10 days, recovery duration= 6 days, and disruption timing= Day 6)

2.3.3.5 Results of Disruption Scenarios

In household-storage-based IWS networks such as the one analyzed in this study, interactions between the four variables that characterize the resilience of the IWS network (namely storage capacity, recovery duration, the timing of the disruption, and the supply scheduling) result in different behavior of the network performance. Figure 2.21 summarizes the results of the network performance over time for different combinations of storage capacities and recovery durations of the two disruption scenarios. The figure shows the results for disruptions that occur on Day 1 of the supply schedule (the beginning of supply to DMZ-1). The results for other disruption timings can be found in Figure A.1, Figure A.2, and Figure A.3 in Appendix A.

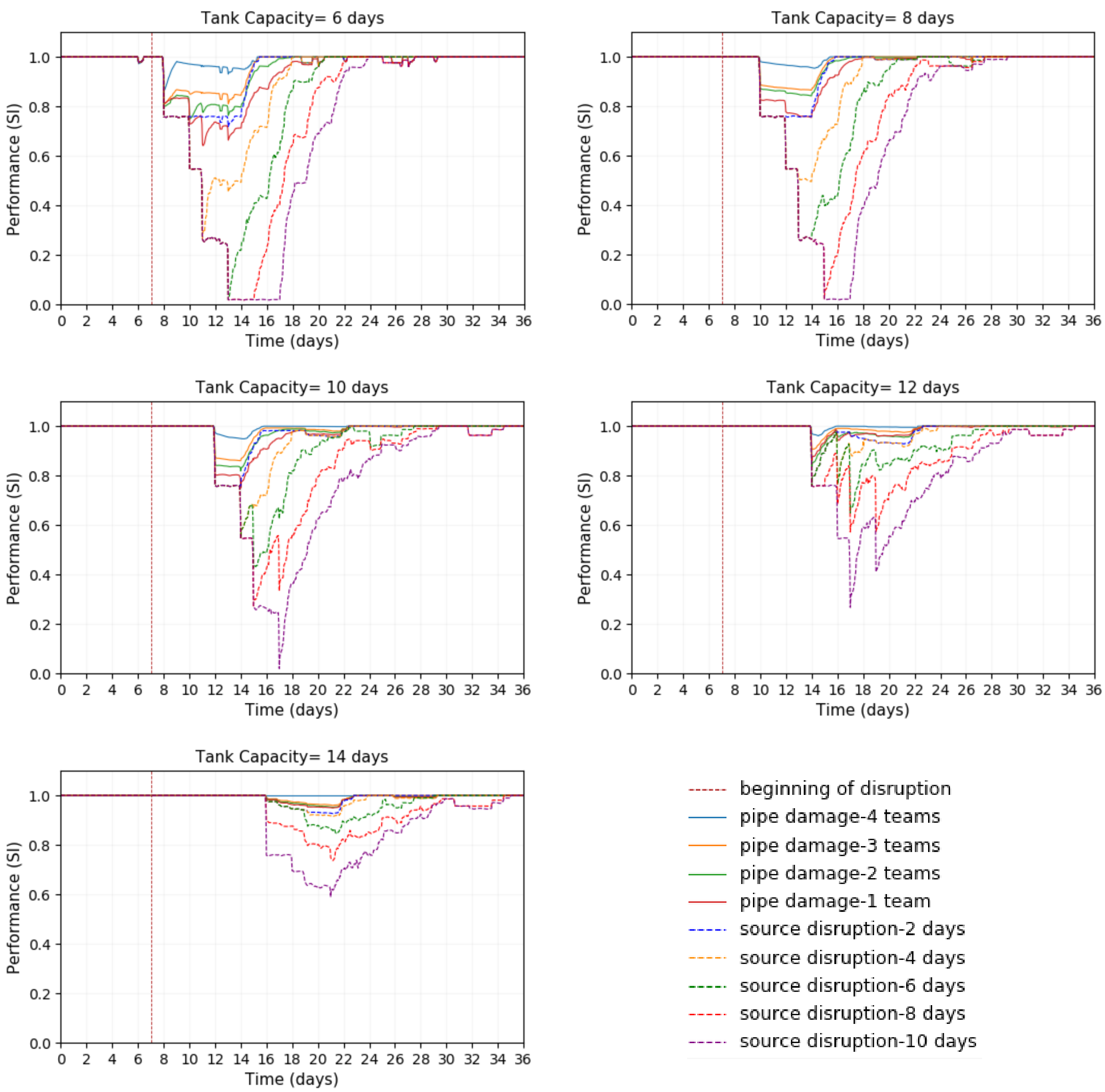


Figure 2.21. Network's Serviceability Index (SI) for different disruption scenarios and household storage capacities (disruption occurs at the beginning of **Day 1** of the supply schedule)

All four variables that affect the network resilience are expressed in terms of time and/or duration (timing and duration of the disruption, the duration of supply by tanks, and times and durations of network supply from the supply schedule). The different interactions between these times and/or durations result in different behavior of the network. For example, greater storage capacities that provide longer backup supply (longer than the recovery duration) would improve the network performance, SI. However, greater storage capacities may require longer supply duration to ensure sufficient supply available to all tanks in the zone to survive through the supply cycle. Therefore, the supply scheduling for each zone becomes relevant in addressing the supply inequity. The timing of the disruption impacts the supply duration required for filling the tanks in the zone due to the heterogeneity of supply inequity among zones in the network.

Comparing Disruption Patterns of IWS and CWS Networks

Due to supply rationing and the existence of household storage tanks, there are three main observed features that distinguish the disruption patterns (i.e., performance loss curves) of IWS networks from the disruption patterns of CWS networks that have been discussed in the literature (e.g., Diao et al. 2016; Guidotti et al. 2016; Aydin 2018; Khatavkar et al. 2019). These features include disruption lag, zone-sensitive performance loss, and post-disruption effects.

- ***Disruption Lag***

While disruption effects are immediate in CWS networks, disruption patterns in IWS networks show a time lag between the occurrence of the disruption and the time of the performance drop. The disruption lag is the result of the storage buffer available in households, and its length depends on the capacity of household storage. If the storage capacity is large enough, households may never experience any disruption of water supply, depending on the length of the network damage.

- ***Zone-Sensitive Performance Loss***

Performance loss in IWS networks is characterized by multiple sharper drops in performance as the impact of disruptions extends to additional zones in the network. While the variation in the quantities of available stored water is low between households within a zone, there is a significant variation in the average quantities of water available in households across different zones (due to supply rationing). This variation across zones results in a larger number of households running out of water within a shorter period of time. This feature can be seen in the form of the step-wise performance loss in Figure 2.21, where each drop in performance represents an additional zone being affected. This feature of IWS networks suggests that the speed of recovery is significant if the disruption of additional zones is to be minimized.

- ***Direct and Post Disruption Effects***

The most significant feature of the disruption patterns in IWS networks is the existence of post-disruption effects, in addition to direct effects that are also found in CWS networks. The difference between direct and post-disruption effects is as follows:

- Direct disruptions (i.e., primary disruptions): household tanks run out of water as a result of the absence of water supply during the designated supply times *during the recovery process*. The occurrence and the length of direct disruptions depend on the storage capacity with respect to the recovery duration.
- Post disruptions (i.e., secondary disruptions): household tanks run out of water due to insufficient designated time of supply *after the completion of the recovery* (i.e., not sufficient supply to allow tanks to get full). Therefore, tanks get empty before they receive the supply of the following cycle(s) (i.e., following week(s)). Greater storage capacities and greater zone's supply inequity contribute to the occurrence and the length of post disruptions. A disruption scenario might have multiple post disruptions until all tanks in the affected networks get sufficiently filled.

Different disruption scenarios might result in one or both of these types of disruptions. Figure 2.22 provides a visualized illustration of the different cases of direct and post disruptions given different interactions of storage capacity, supply scheduling, and network damage for a specific disruption timing. Although the types of disruption effects (direct and post) may be easily expected for a specific disruption scenario combination by comparing these three factors, the magnitude of the loss in network performance depends on interactions that are captured by hydraulic modeling. Direct disruptions are irrelevant to supply inequity, and thus the impact of direct disruption on a household depends only on the storage capacity of household tanks. In this example, the impact of direct disruptions is equally distributed between households in the zone since all tanks have equal storage capacity. On the other hand, the impact of post disruptions depends on both the storage capacity at individual households and the storage capacity of other households in the zone. Therefore, each type of these disruption effects should be addressed differently when planning for resilience enhancement of the network.

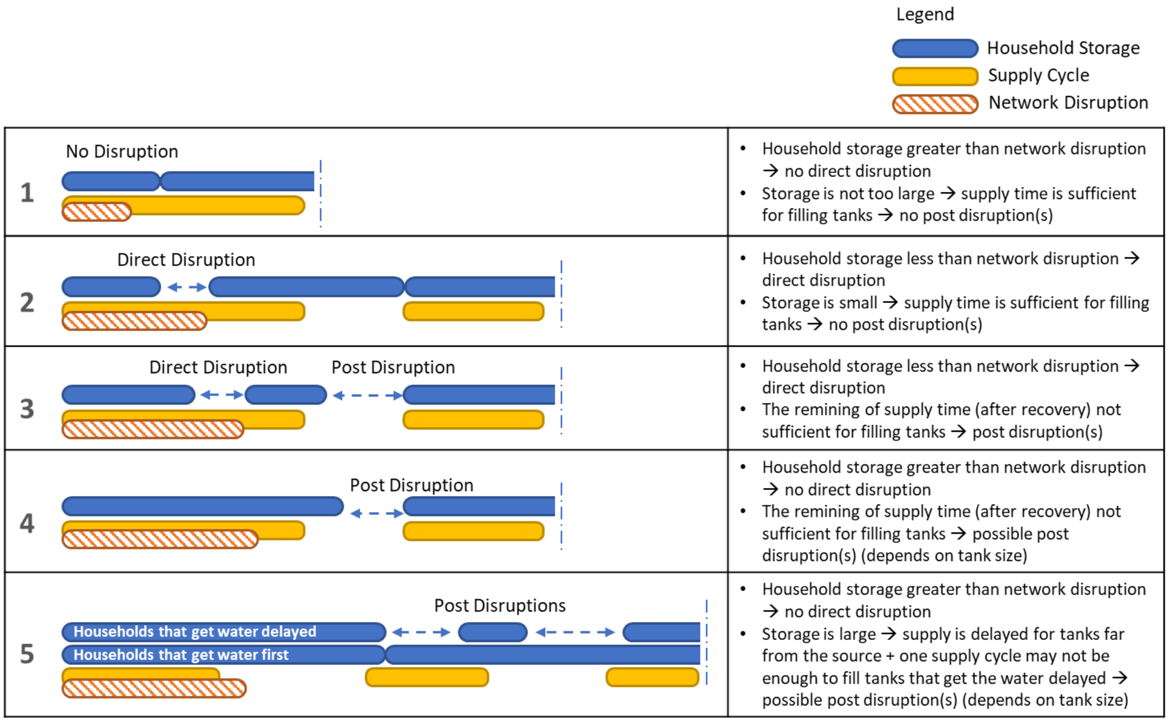


Figure 2.22. Illustration for different cases of direct and post disruptions for a specific zone

Analysis of Overall System Resilience (OSR)

The OSR represents the ratio of the network performance (in terms of the actual demand satisfaction) during the disruption to the normal operation performance (using Equation 2.4). For each scenario run, the area under the disrupted performance curve is calculated and divided by the time (assuming 100% normal operation performance). The time span in which the OSR is assessed within (i.e., the duration that is used to calculate the OSR) has an impact on the scale of the values of the OSR. For this analysis, a time span of 3 weeks, starting from the beginning of the network disruption, was used to allow comparisons between all scenarios' combinations. As a result, differences between the results of shorter disruptions (e.g., those lasting a week or so) may appear to be small in magnitude since the effects are evaluated over a 3-week performance period. Figure 2.23 summarizes the OSR results for all pipe-damage scenario combinations (varying the storage capacity and the recovery resources) and for all source disruption combinations (varying the storage capacity and the deterministic recovery durations).

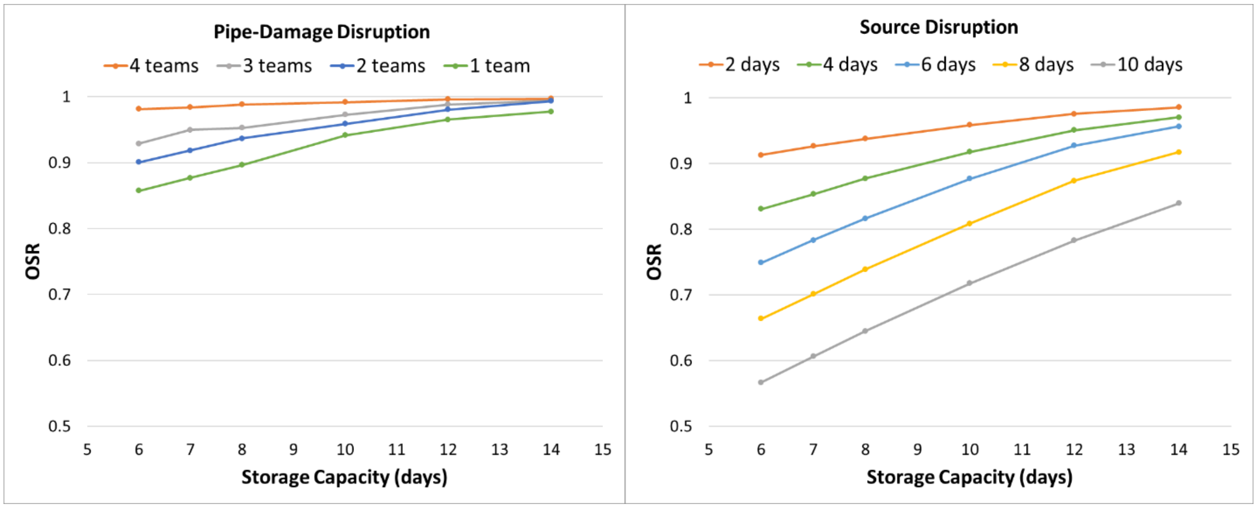


Figure 2.23. OSR vs. Storage Capacity for different recovery resources/durations (Each point in the figure on the left represents the mean of Monte Carlo simulation)

For all recovery scenarios, Figure 2.23 shows that the network resilience increases (on average) as the storage capacity increases as expected. In addition, it is also intuitive that network resilience increases with faster recovery, as shown in the figure. However, the results show that when the network has lower household storage capacities, the improvement in resilience resulting from having faster recovery is greater. In other words, the effectiveness of increasing the speed of recovery (in terms of improving the resilience of the network) is a function of the current network's performance, and the lower performance of the network, the greater the effectiveness of speeding up the recovery. This behavior reflects the fact that disruptions of the greater-storage-capacity network are mainly post-disruptions that depend on supply inequity in addition to the length of the network damage. On the other hand, a lower-storage-capacity network is more prone to direct disruptions that depend only on the speed of recovery. This result is shown clearer in Figure 2.24 that details the results for different timings of the disruption (where each timing represents the worst timing for a zone), for different combinations of storage capacities and recovery resources for the pipe-damage scenario (and for the source disruption scenario in Figure 2.25). As can be seen in both figures, the 6-day storage capacity (orange bars) shows a greater increase in the OSR value as the recovery resources increase, and the rate of increase in improvement in OSR decreases with greater storage capacities.

The network shows a variation in the OSR for different timings of the network damage. For a given recovery speed, zones in the network show different responses to the same damage. This variation is attributed to the zone hydraulic and topology attributes, in addition to the supply inequity within the zone, as explained earlier. For example, network disruptions that target DMZ-1 and DMZ-4 result in a relatively greater impact on network performance since these two zones have a higher supply inequity compared to DMZ-2 and DMZ-3. The results also show that although on average, the rate of resilience improvement is correlated with lower storage capacities, different zones (experiencing different timings of the network disruption) respond differently in terms of the rate of improvement in the network's resilience when speeding up the recovery process. For example, for the 6-day storage capacity in Figure 2.24 (in orange), disruption timings of Day-1 and Day-6 for one team of recovery resources (top-left part of the figure) resulted in closely similar values of OSR (around 85%) but the OSR for Day-1 timing improved by 5% when 2 teams of recovery were used, while the OSR for Day-6 improved only by 2.5%. This variation between different disruption times depends on which zones' scheduled supply gets affected during the disruption, especially if the disruption extends to affect more than one zone. This finding shows that the supply order of the zones in the supply schedule have an impact on determining the network's resilience and the effectiveness of speeding up the recovery process.

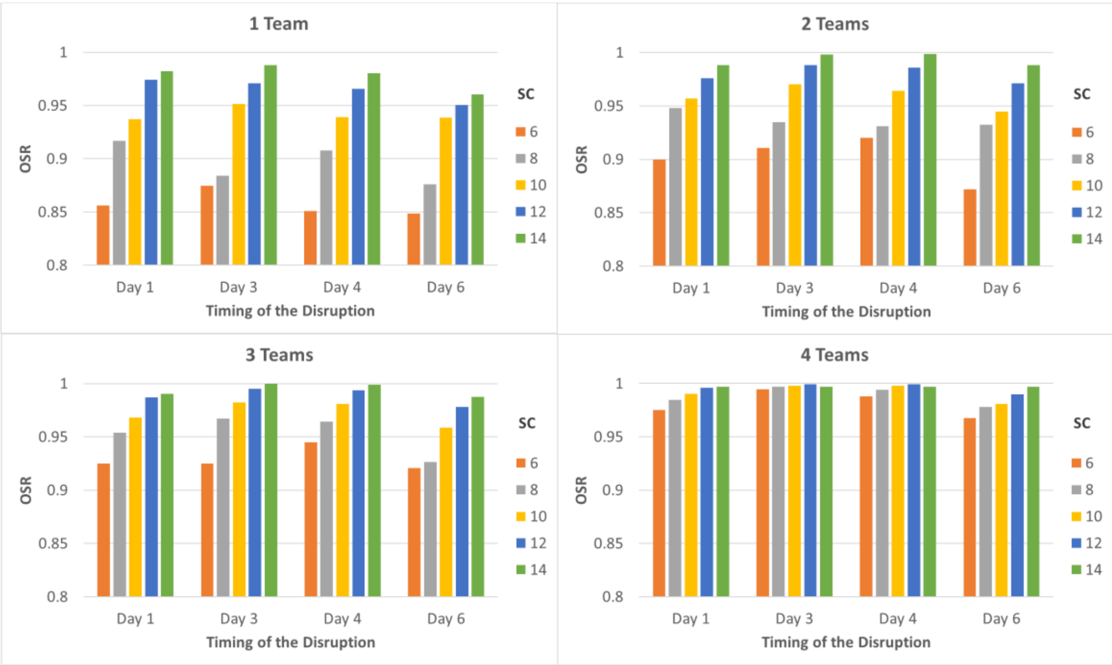


Figure 2.24. OSR for all combinations of the pipe-damage disruption scenario (SC: storage capacity in days)

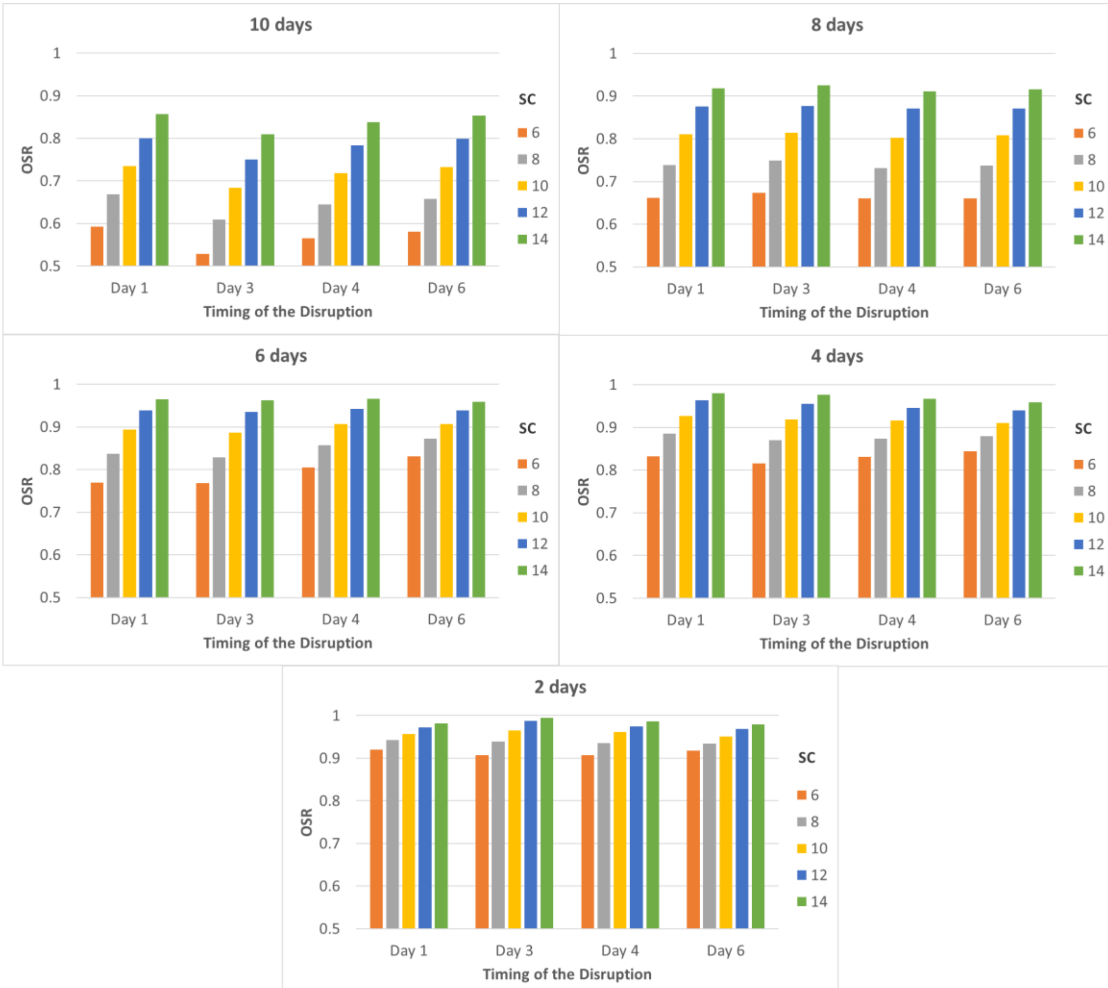


Figure 2.25. OSR for all combinations of the source disruption scenario (SC: storage capacity in days)

Analysis of the Related Network Performance Measures

In addition to the two performance measures that are used in the resilience calculations (SI and ATFR), there are other measures of network disruption that are of interest to the utility. One commonly used measure is the number of affected consumers. When compared to the OSR, this measure shows the distribution of the impact of the disruption among households. Figure 2.26 shows the number of affected consumers (those whose water storage is completely depleted) for each combination of the damage-pipe scenario and the source disruption scenario. The results show that the number of affected consumers increases as the recovery duration increases since the disruption will extend to more than one zone. However, for a certain scenario of damage duration, the storage capacity seems at first irrelevant to the number of affected consumers (the number of affected consumers starts at a higher value at 6-day storage capacity then stays at an almost constant value until dropping when reaching a storage capacity of 14 days). However, this trend can be explained by the relationship between the storage capacity and the supply schedule. As the storage capacity extends to a new supply cycle (every 7 days), a reduction in the number of affected consumers is expected. As shown in Figure 2.26, source disruptions of 2, 4, and 6 days affect one supply cycle, and a 14-day storage capacity would limit the effect of these disruptions to a limited number of affected consumers (less than 50). However, source disruptions of 8 and 10 days affect two supply cycles, and thus a storage capacity greater than 21 days will be required to bring the number of affected consumers below 50.

Another measure of network performance related to consumers is the duration when consumers are affected. If the storage capacity increases, the network resilience (OSR) improves even if the number of affected consumers does not change because consumers experience shorter disruptions (i.e., water runouts). Figure 2.27 shows the total consumer disruption hours (aggregated number of hours each consumer spent without water) for each combination of the damage-pipe scenario and the source disruption scenario (different storage capacities and different recovery durations). The results in the figure show that total consumer disruption hours decrease with greater storage capacities even when the number of affected consumers is unchanged, which explains the improvement in the network's resilience with greater storage capacities.

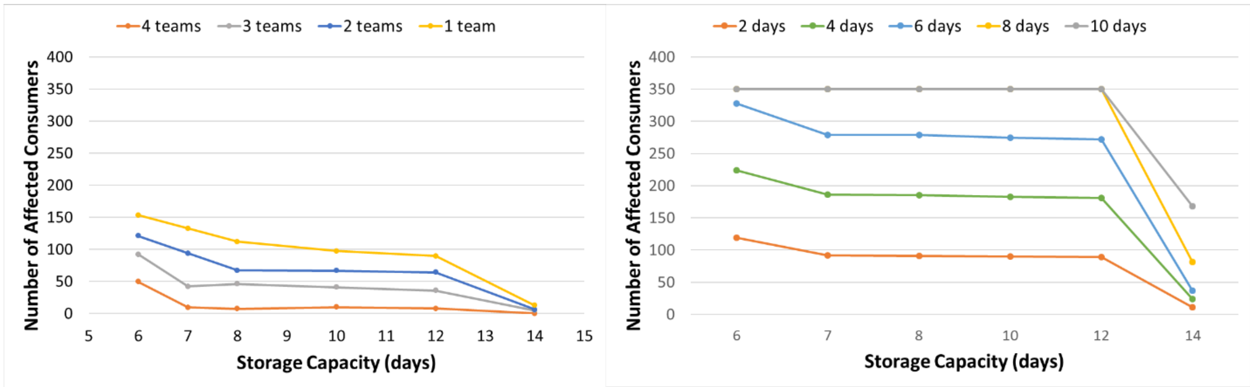


Figure 2.26. Number of affected consumers for different combinations of storage capacities and damage durations for the two disruption scenarios

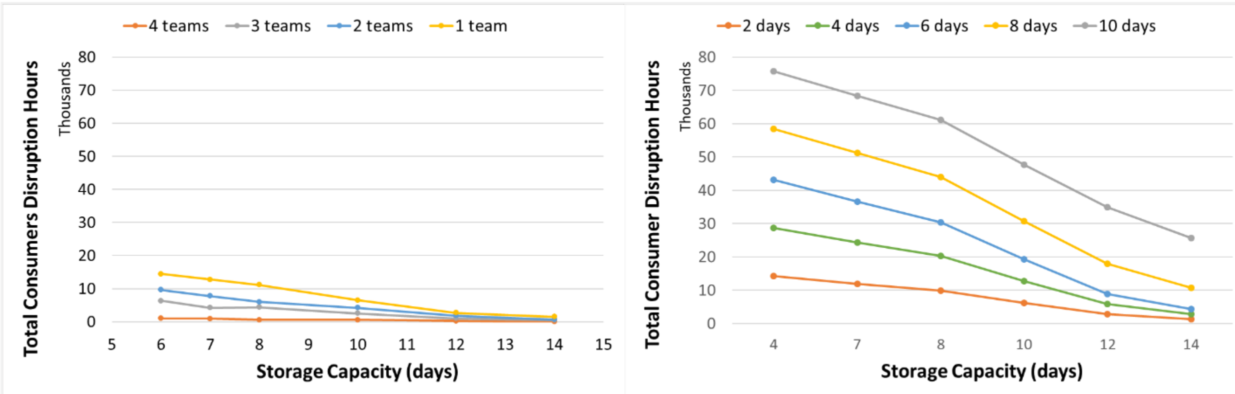


Figure 2.27. Total consumer disruption hours for different combinations of storage capacities and damage durations for the two disruption scenarios

Another network performance measure that is of interest to the utility is the disruption duration. Disruption duration is defined as the duration during which the network performance (i.e., SI) was below 99%. As seen in the results of the analyses in previous sections, the network-disruption duration can be greater (or less) than the network-damage duration. Figure 2.28 shows the disruption duration for each combination of the damage-pipe scenario and the source disruption scenario. The results in Figure 2.28 show that increasing the storage capacity can result in either an increase or decrease in the disruption duration since this behavior is a result of the interplay between storage capacity and the recovery duration. In general, increasing the storage capacity decreases the disruption duration, as seen in the curves for the pipe-damage scenario and the 2-day curve for the source disruption scenario. However, when the post-disruption effect is introduced, the disruption duration increases accordingly until the storage capacity becomes sufficient enough to minimize the overall effect of the disruption.

These three performance measures have different implications in the decision-making for the utility. For example, the utility may aim to minimize the number of affected consumers (even if it results in longer durations of inconvenience to consumers) by providing water from a non-piped source. On the other hand, the utility may be interested more in having an overall shorter disruption duration for the whole network regardless of who is being affected and for how long. The utility could also examine different recovery scenarios to balance these three measures in addition to the resilience metrics to suit their objectives.

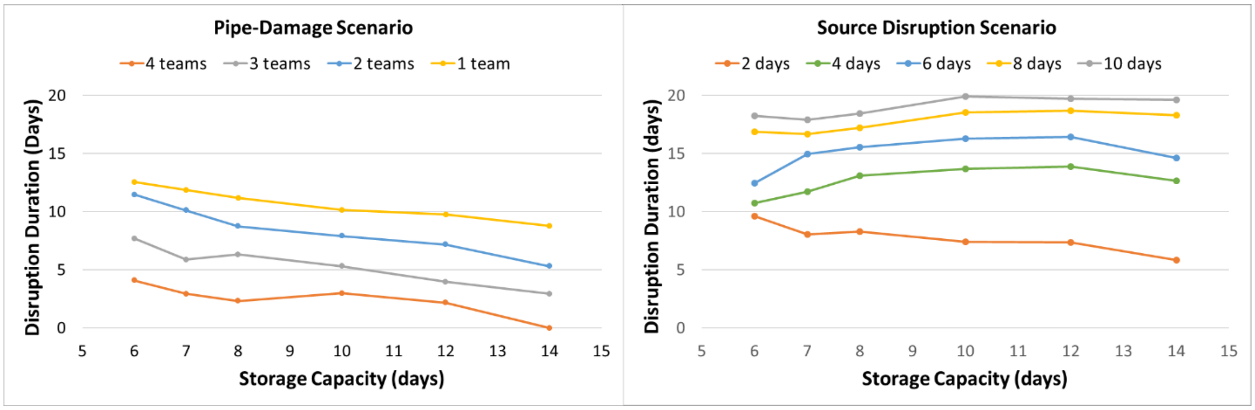


Figure 2.28. Results of disruption duration for different combinations of storage capacities and damage durations for the two disruption scenarios

Analysis of the Absorptive Resilience Capacity

Absorptive resilience is determined by the retained ATFR (that captures the ability of the network to withstand disruptions) and the retained SI (that captures the ability of the network to minimize the impact of disruptions). Figure 2.29 shows the results of the absorptive capacity as the storage capacity increases for different recovery durations for the two disruption scenarios. Each point in the figure is the absorptive capacity calculated by Equation 2.5 assuming equal weights for the retained SI and the ATFR. The sharper increase in some of the curves arises from the sudden improvement of the retained SI as a sign that the increase in storage capacity (and/or in the recovery speed) resulted in avoiding disruption in one of the zones. The results in Figure 2.29 can be adjusted by assuming different weights of the SI and the ATFR in order to evaluate a disruption scenario. If the utility is more interested in preventing disruptions, they could assign greater weight to the AFTR. On the other hand, if the utility cares more about maintaining a minimum level of performance during the disruption, a higher weight can be assigned to the retained SI.

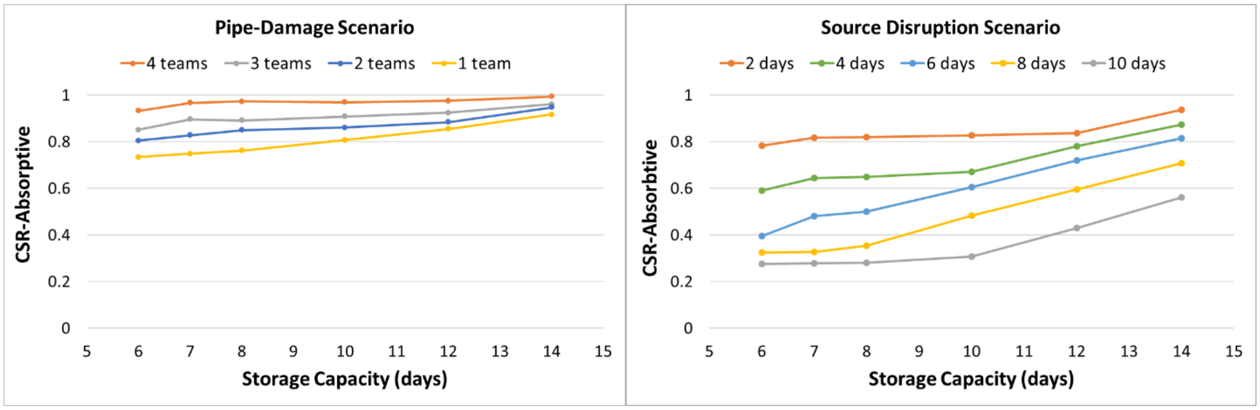


Figure 2.29. Results of absorptive resilience capacity (CSR-AB) for different combinations of storage capacities and damage durations for the two disruption scenarios

Analysis of the Restorative Resilience Capacity

Restorative capacity is the probability of the network to meet a pre-defined target of recovery time for a given disruption scenario. The network is considered recovered when the level of performance of the network returns to the pre-disruption level (i.e., at least SI =99%). The recovery time is calculated from the time where the network's performance drops below 100% until the time it reaches back to above 99%. Restorative capacity is only relevant to stochastic disruptive events (e.g., pipe-damage scenario), and the variation in the recovery times for a given recovery strategy is due to the uncertainty in the location and the criticality of the initially failed pipes. For the source-disruption scenario, the restorative capacity will be deterministic (similar to the disruption itself). The results for the restorative capacity for the pipe-damage scenario are shown in Figure 2.30. While varying the predefined target for the recovery time, each curve in the figure shows the probability of meeting the time target for a certain storage capacity and recovery resources. The probability of meeting a time target is calculated (using Equation 2.7) based on the 100 stochastic-simulation runs and averaged for the four disruption timings. The results show that with faster recovery, the network is more likely to meet the predefined time targets (i.e., reach a value of 99%). However, for the storage capacity, the relationship is more complicated and depends on the interactions between the storage capacity and the recovery resources that result in different cases of direct and post disruptions (Figure 2.22).

The results of the restorative capacity in Figure 2.30 can assist the utility in evaluating the effectiveness of different recovery strategies. The current practice of utilities focuses mainly on the speed of recovery when planning for recovery strategies. However, when recovery resources are limited, the analysis of restorative capacity can assist in planning to maximize the effectiveness of these resources. For example, if the recovery time target is 8 days and the storage capacity is 10 days, the probability that the network would recover before 8 days would increase from 0.35 to 0.63 if recovery resources are increased from two to three teams.

The analysis of the restorative capacity can also assist utilities in understanding the variation in the criticality of the network's pipes and their repair requirements. In addition, it can help the utility in the long-term planning by estimating the impact of increased/decreased household storage capacity on the ability of the network to meet the recovery time targets.

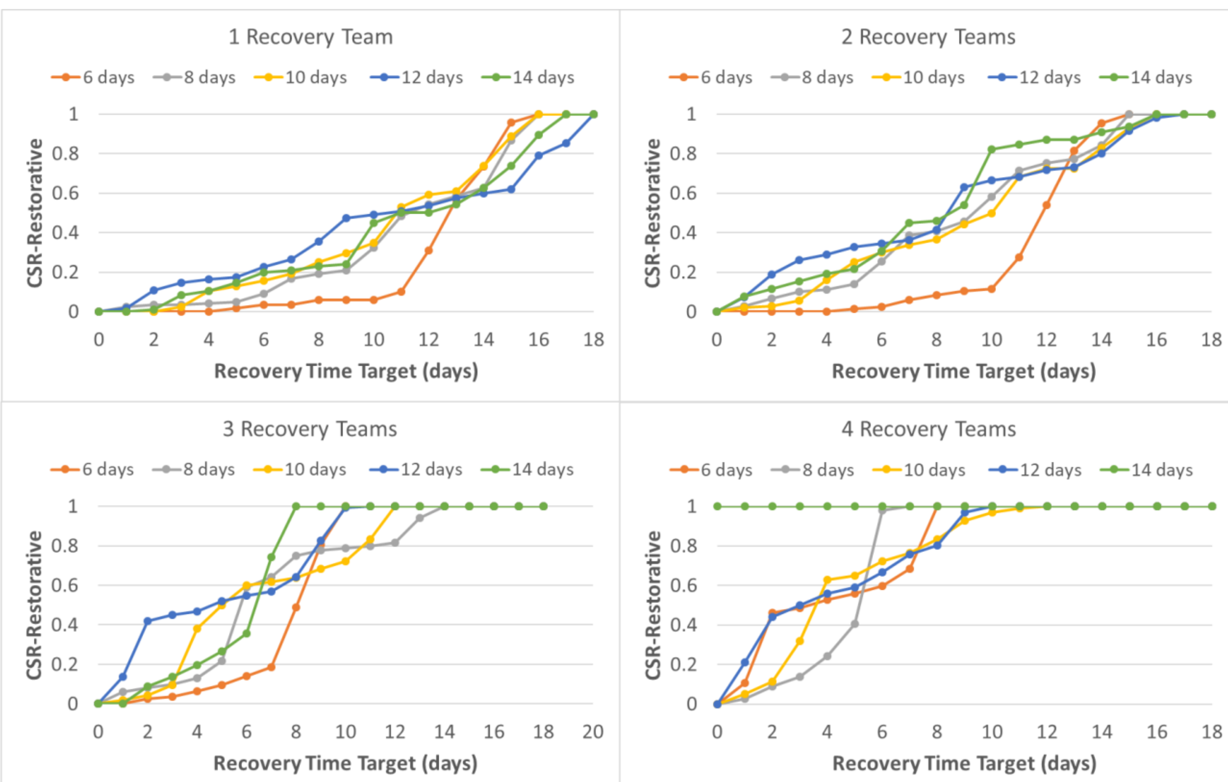


Figure 2.30. Restorative resileicne capacity for changing recovery time target for different storage capacities and recovery resources

The reliability of the results of the restorative capacity depends mainly on the representativeness of the recovery strategy. For this research, a generalizable recovery strategy proposed by HAZUS-MD (a multi-hazard loss estimation methodology developed for FEMA) is used. Average restoration times were validated using actual restoration data for the analyzed sub-network obtained from the utility in the case study city. However, the utility can use its own recovery strategy (i.e., based on pipe prioritization, number and productivity of recovery teams, etc.) to estimate the restorative capacity.

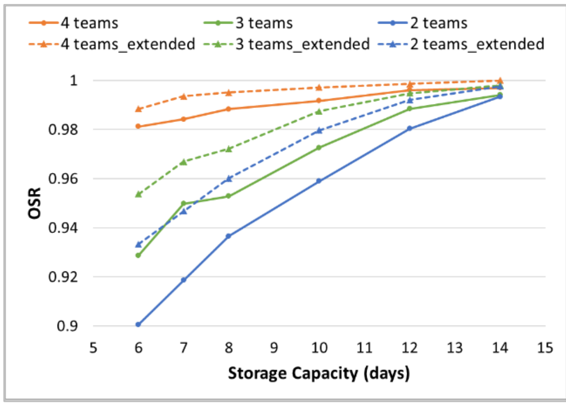
2.3.4 Analysis of the Utility Adaptive Behavior during Disruptions

Since prior studies on the analysis of the resilience of water supply networks have focused on CWS systems, the behavior of the utility during network disruptions was limited to the restoration efforts of the failed system's components. However, in addition to recovering the damaged components of the network, the water utility in IWS networks can take temporary adaptive measures to improve the network's performance during the disruption. This section analyzes the *short-term supply schedule modification* as the utility adaptive measure to define the parameters that determine the effectiveness of such strategy.

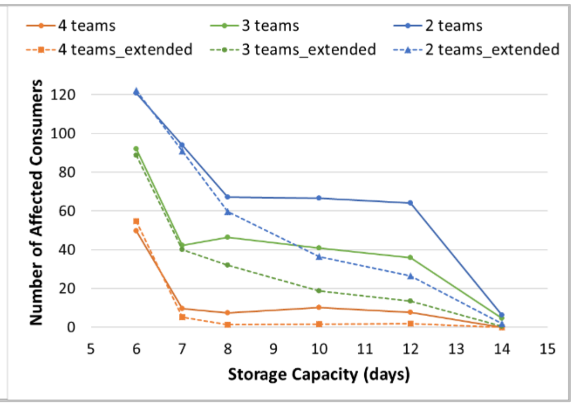
The strategy of extending the supply to affected zones is evaluated as a practical measure that extends the supply for the affected zone(s) without changing the supply for other zones. Supply extension is a practical strategy in terms of implementation since it requires no additional human effort to apply (given that the zones' isolation values are operated manually in most IWS networks. Supply extension takes effect right after the completion of the restoration efforts, assuming that affected zone(s) cannot benefit from any changes in the supply schedule during the network damage.

The resilience quantification model for IWS networks was modified to allow dynamic changes to the static supply schedule to provide affected zone(s) with an extended supply of 24 hours after the completion of the restoration efforts while keeping the supply to the unaffected zones unchanged. No changes to the supply schedule were implemented for simulation runs that resulted in no affected zones. The idea of supply modification relies on the storage buffer in the network. Therefore, disruptions that impact the performance of all zones were excluded from the analysis (i.e., the scenarios of using only one recovery team).

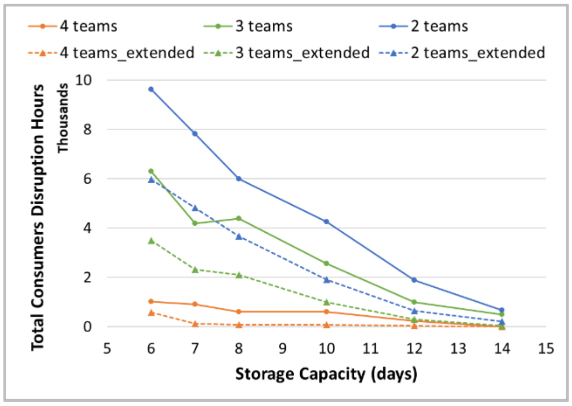
Figure 2.31 shows the results of OSR, the number of affected customers, and the total consumers' disruption hours for the original and the modified schedule. The supply extension resulted in improved network resilience for all evaluated combinations of storage capacities and recovery resources. The results of the OSR show that it is possible, by modifying the schedule, to achieve a network-resilience that is greater than the improvement resulting from increasing the recovery resources (e.g., from 2 teams to 3 teams). The improvement in the OSR depends on the storage capacity where lower storage capacities benefited more from the 24-hour supply extension due to the lower effect of supply inequity. The results also indicate that the mechanism in which the network benefitted from the supply extension is different based on the storage capacity. For greater storage capacities (e.g., 8 days, 10 days, and 12 days), the network benefited from the supply extension mainly by decreasing the number of affected consumers. On the other hand, for lower storage capacities (e.g., 6 days and 7days) there was no (or very limited) reduction in the number of affected consumers, but the reduction in the total consumers' disruption hours show that affected consumers experienced shorter disruption durations due to supply extension.



(a)



(b)



(c)

Figure 2.31. Results of (a) OSR, (b) number of affected consumers, and (c) total consumers disruption hours for the original and the modified schedule (supply extension for the affected zone(s))

2.4 Verification and Validation

The verification and validation for the developed framework were done in three steps: validating the conceptual model, verification of the computerized model, and external validation with relevant studies in the literature. Validating the conceptual model was done through face-to-face meetings with water experts from the city in December 2018 and in January 2019. A total of 8 experts of the water supply system, including university professors, utility engineers and managers, hydraulic modelers, and water consultants) with at least 8-year experience with the systems, were involved in the verification and validation. The experts verified the model assumptions, logic, and relationships as logical and representative. The chosen subnetwork for the case study was verified as a representative subset of the city's water network. The assumed supply schedule was based on the utility's practice.

The verification of the computerized model was done first by verifying the intermediate results for each model step. In addition, the model was developed in three stand-alone phases. In the first phase, a model for quantifying the resilience of CWS systems was developed, which allowed the verification of the disruption-recovery simulation. A hydraulic model was then developed to simulate the normal operation of the IWS network, and the process of supply scheduling and the filling of household tanks was verified. Finally, the two models were combined to assess the resilience of IWS systems against physical disruptions. The results of varying the model parameters (storage capacity, recovery speed, and disruption timings) were consistent and logical. Testing of extreme values was done to ensure a consistent model response. The detailed results of each of the combinations of the two disruption scenarios were carefully examined, and the explanation of any unexpected behavior was tested and verified.

Regarding external validation, one of the main challenges in modeling the resilience of water supply networks is the very limited availability of real-system data to validate the resilience analysis model. Resilience models of water supply networks often require detailed data about the performance of the network at a greater resolution (e.g., in hours), which are either never collected by the utility during normal operation, or the data is limited to the restoration times for failed pipes. Another challenge in validating resilience models is that these models simulate the behavior of the water network against some disruptive events. Although performance data such as the flow and the pressure can be theoretically available for some nodes in the network (using the data from flow and pressure gages), data related to failure assessment and recovery efforts (such as number and location of pipe breaks and the timing of correcting failures) are less likely to be recorded.

Another type of data that is usually available by the utility is the supply and demand data in the form of the readings of water meters that record the inflow from the WDN to household tanks. Aggregated supply and demand data over time may reveal some useful patterns for the validation of the network's performance under normal operation conditions. However, supply and demand data are often not linked to disruption data. In other words, disruption data recorded by the utility does not indicate which households were affected by the disruption and/or the duration of the disruption for the household. In addition, the supply intermittency makes it difficult to differentiate household supply shut-offs that are due to disruptions from those due to changes in supply scheduling since supply scheduling often changes (as indicated by the responses of the household survey in Chapter 3). In addition, household supply includes the supply from non-piped sources, which is not recorded (and may be unknown) by the utility, and which makes the data from water meters not representative of the actual household supply during disruptions.

A sample pipe failure data for the studied subnetwork was acquired from the utility in the case study city. This data was used to validate the recovery process in the model in terms of average times of pipe repairs. However, the pipe failure data was limited to the location of failed pipes and their required repair times, and it was not linked to the household supply data.

The resilience model was validated by confirming the consistency of the results with published literature (Table 4.4). In addition, three of the subject matter experts validated the results of filling times for household tanks as being reasonable.

Table 2.4. External validation

Relevant Finding/Discussion	Study(s)
The existence of household storage affected the network' operation due to the unique demand pattern of storing as much water as possible during the supply period	Ingeduld et al. 2006; Mohapatra et al. 2014
Supply to consumers is inequitable in IWS networks due to excess water withdrawal by households	Ameyaw et al. 2013; Soltanjalili et al. 2013; Gottipati and Nanduri 2014; Mohapatra et al. 2014
Supply inequity exists within and between demand zones	Guragai et al. (2017)
The impact of pipe failures is not equally distributed among consumers in the network	Gheisi and Naser 2015
Changes in the supply schedule can improve the network performance in terms of demand satisfaction	Ilaya-Ayza et al. 2017

2.5 Conclusions

This chapter introduced a new framework for assessing the resilience of IWS networks. The framework addresses IWS systems that are characterized by household storage where consumers rely on the piped network as the main source of water supply. Two resilience metrics, namely overall system resilience and capacity-specific resilience, were introduced to evaluate the overall system resilience and to explain the contribution of the three resilience capacities (absorptive, adaptive, and restorative) against acute physical disruptive events. Two performance measures (the Serviceability Index and the Network-Average Tank Filling Ratio) were used to estimate the resilience metrics, and to explain the network's response at all stages of the disruption-recovery cycle. The framework was evaluated and its viability was validated in the context of a case study from the water network in a city in the Middle East.

The framework was able to explain the system behavior at all stages of the disruption-recovery cycle. The analysis of the results explained how the two different performance measures, SI and ATFR, can explain the network behavior at different points on the disruption-recovery cycle. The SI is helpful in understanding the extent of the disruption on the consumers' end. SI, as a performance measure, is of importance to the network operator as it is an indicator of the reliability of the water service. However, the SI fails to capture the effect of some of the disruptions that were absorbed by the available household storage, and this effect was only explained by the reduction in the ATFR.

The resilience metrics (OSR, CSR-AB, CSR-AD, and CSR-R) were able to quantify the different resilience capacities of the water network. The OSR have shown the collective effect of all types of resilience aspects in the system, which include robustness, reliability, adaptability, and resourcefulness. On the other hand, CSRs explain how each type of these resilience aspects contributed to the overall system resilience. Robustness and reliability are captured by the absorptive capacity, adaptability is captured by adaptive capacity, and resourcefulness is captured by the restorative capacity. The CSRs represent the contribution of each resilience capacity toward the overall system capacity.

2.5.1 Summary of Findings

The analyses in this chapter revealed new insights regarding the resilience of IWS infrastructure systems. The findings in this chapter are related to (1) supply inequities, (2) direct and post disruption effects, and (3) the influence of interdependent factors affecting the resilience of the system.

The supply inequity in IWS networks occurs at the zone-level and at the network-level. The zone-level supply inequity between households depends on household storage capacities and the network layout within the zone. Greater household storage capacities lead to greater supply inequity as a result of longer tanks' filling times. The network layout within the zone affects the degree of interdependency between the filling times for household tanks. The network-level inequity depends on the zone's location and connectivity to the water sources of the whole network. Greater number and sizes of zone's inlet pipes and greater pressure at the zone's inlets result in a faster filling of household tanks and lower supply inequity among households.

The occurrence and the intensity of direct and post disruption effects depend on the interactions of storage capacity, supply scheduling and the length of network damage. Different combinations of these three factors can result in direct and/or post disruption effects. Direct disruptions were found dependent on the storage capacity of households with respect to the length of the network damage. Therefore, direct disruptions were found associated with smaller household storage capacities. On the other hand, post disruptions are caused by supply inequity among households. Thus, larger storage capacities resulted in more post disruptions due to the greater impact of supply inequity.

The response of the IWS network to disruptions show that household storage capacity, recovery speed, supply scheduling, and the timing of the occurrence of the disruption (with respect to the supply schedule) determine the resilience of the network. The interactions between these variables caused different combinations of direct and post disruptions, which in turn creates non-linear trends of the number of affected consumers and disruption duration. By changing the timing of the occurrence of the disruption, the results showed that each zone response differently when being affected by the disruption due to having different levels of supply inequity. Thus, the loss of performance for the network is affected by the timing of the occurrence of the damage.

Greater household storage capacity and faster recovery both found to improve the network's overall resilience (OSR), but the level of improvement was found to be associated with the current network's performance (the lower the performance, the greater the improvement). The resilience of the network improves as a result of the reduction of the number of affected households and/or the reduction of the household's duration of being affected.

The results in this chapter highlighted a possible trade-off between the resilience of the network and the duration of the effect of the disruptions. For instance, the combination of longer damage durations (greater than one supply cycle) and greater storage capacity resulted in greater network's resilience but led to longer durations of disruption (i.e., longer durations during which demand satisfaction was below 99%). This trade-off is caused by the re-emergence of post disruptions (even after reaching 100% demand satisfaction). The results showed that it may take more than 3 weeks of normal operation of the network following the disruption in order to completely eliminate the effect of post disruptions depending on the level of supply inequity.

2.5.2 Contributions to the body of knowledge

The main contribution of this chapter to the body of knowledge is the development, evaluation, and validation of a framework for the analysis of the resilience of IWS systems. The framework makes the contribution of defining and evaluating resilience measures that assess the *overall effect* of resilience aspects along with the *contribution* of each resilience capacity. The framework also adopts a combination of performance measures that capture the system's behavior at *all* stages of the disruption-recovery cycle. The evaluation of the framework also contributes to the body of knowledge by identifying the interactions of main factors that determine the system's resilience.

2.5.3 Contribution to the body of practice

The framework can assist the water utility in the operation of the IWS network under normal conditions. IWS networks are often operated based on personal experience of utility personnel simple demand and supply trade-off analysis (Ilaya-Ayza et al. 2017). However, the utility can use the hydraulic simulation process provided in this framework and the analysis of supply inequity to explore different operation strategies to improve the network performance. These strategies may include decreasing water demand at nodes very close or far away from the source, increasing the diameter and addition or elimination of some key linking pipes in the WDN (Gottipatiand and Nanduri, 2014). The framework can also assist water managers in testing different scenarios of network disruptions (different disruptive events, supply schedules, household storage capacities) and assess their impact on the network's resilience to plan for long-term resilience enhancement strategies. In addition, the results of the presented analyses can assist the utility in the short-term response to network disruptions (recovery resources, modification of supply schedules). The utility can use the proposed framework and the evaluated variables in the planning for anticipated or planned disruptions of the IWS network (e.g., pipelines maintenance, inspection or replacement) by choosing the timing and the length of the disruption and identifying affected parts of the network in order to minimize the consequences of the disruption. Another contribution to the body of practice is that the framework can assist in determining the critical assets in the network that have higher priority for enhancement/rehabilitation due to the greater impact of their failure on the network performance.

2.5.4 Limitations and Future Work

The presented work in this chapter has some limitations. First, the framework is implemented in an IWS network that relies on underground household tanks controlled by floating valves. The framework can be modified to address the specific configurations of household storage and/or supply scheduling schemes of other IWS systems. In addition, the network damage in the demonstrated case study was limited to pipelines. However, the framework is expandable to allow the modeling of the damage and the recovery of other network components (such as pumping stations, tanks, and treatment plants)

The capacity of household storage was assumed to be equal for all household tanks in the network. This allows a variation in filling the tanks (since tanks have different volumes) but limits the variation in the running-out of water (since households have similar storage capacity in terms of the number of days) to make it possible to interpret the effect of other variables. Nevertheless, the framework allows one to specify different capacities of household storage tanks.

One of the limitations is that the analysis is based on one representative supply schedule and duration that is fixed for all combinations of scenarios in order to limit the variation in the results to other variables, namely, household storage capacity, recovery speed, and the timing of the occurrence of the disruption. Nevertheless, similar underlying relationships may be expected for different supply schedules. However, testing different intermittent water distribution schemes (e.g., time-based at the zone-level, time-based at the household-level, quantity-based at the household-level) will be important to confirm and further analyze these results. This type of analysis will be relevant to smart water networks since some of these schemes could be soon realized by the advancement in smart water metering.

Future research can expand the analysis of the resilience of the IWS networks against a wider range of disruptive events. For example, different percentages of the initially failed pipes can be evaluated to test the network's sensitivity to the damage intensity. In addition, the framework can be expanded to include disruption events to other infrastructures that can cascade to the IWS network due to the interdependency relationship. One particular example is the analysis of the IWS network dependency on the power network both in the supply side (the operation of the water network) and on the demand side (the household dependency on electricity for water extraction from household tanks).

Future work can also include the analysis of a city-scale IWS network with a greater number of demand zones and greater variation in zones' attributes (such as size, elevations, and topology) to confirm and/or enhance the results of the presented analyses. The demonstration of the presented model on a small sub-network helps in determining the significant factors that can be used to abstract the whole city's network while preserving the functional aspects of the network. For instance, supply inequity for zones can be described using normal distributions requiring only the mean and the standard deviation of the time required to fill tanks in the zone. Thus, zones can be represented as one "giant" node in the network. This aggregation of the network attributes allows the analysis of the whole network while preserving household heterogeneity in terms of supply inequity.

One of the limitations of hydraulic modeling is the need for computational power. In this study, the average computational time required to complete one run of the simulation of the network damage and recovery (for 4 weeks of simulation time and at one-hour time step) was 2.6 minutes (using Intel Core i7-8665U with 32 GB RAM). Another limitation of hydraulic modeling is the need for detailed information about the network parameters such as pipe diameters, elevations, and connections. These limitations of hydraulic modeling suggest that developing simpler models that can simulate the water supply and demand in WDN operated with IWS. These simpler models should capture the household heterogeneity in terms of supply inequity and storage capacity. One of the recent modeling approaches that has the potential of capturing and explaining the aspects of IWS is network functional mapping (dual-mapping) (Krueger et al. 2017), where network pipes are modeled as nodes and pipe connections are modeled as links. Krueger et al. (2017) concluded that functional mapping provides a more accurate representation of the water network (compared to conventional network modeling) that can explain the network's resilience. Although some of the findings in this chapter could have been reached using functional mapping, there are two pressure-dependent aspects of IWS that required the use of hydraulic modeling: (1) pressure-dependent filling of household tanks and (2) the resulting supply inequity among households. These two aspects are the source of the unique behavior of IWS networks discussed in this chapter. For instance, post-disruption effects (which depend on supply inequity) would not have been observed without hydraulic modeling. The results of this research, using hydraulic modeling, assists in determining the parameters that characterize the supply inequity, and provides a method for explaining supply inequity among households within zones using the normal distribution of the time required for filling household tanks. This abstraction of supply inequity can help future applications of simpler network models (such as functional mapping) while preserving the heterogeneity in supply for households. Thus, this framework serves as a starting point towards developing a robust, scale-free resilience model for IWS systems.

3. ANALYSIS OF SHORT-TERM BEHAVIOR OF HOUSEHOLDS IN INTERMITTENT WATER SUPPLY SYSTEMS DURING DISRUPTIONS

[A version of this chapter was published in the proceedings of the World Environmental and Water Resources Congress 2020.][4]

During physical disruptions of the IWS network, the variables that affect consumer decisions related to obtaining non-piped water are dynamic, and consumer decisions are affected by the attributes (in particular, length and intensity) of the disruption. This chapter analyzes the short-term decision-making process of residential water consumers in a city in the Middle East. In this city, households have long adapted to the intermittency of water supply by installing household water storage with various capacities. However, the volumes of the stored water are often not sufficient to supply the regular household demand for the duration of the disruption, and households have to take actions regarding their water supply and/or water consumption. Based on the results of a survey of more than 250 households in this city, a set of Binary Probit Models were developed to model consumer's decisions related to the timing of their responses to the disruption, their willingness to pay for faster delivery of water using tankers, and their willingness to pay to avoid waiting in-line at the tankers' location. The results of the analysis show how variables such as household characteristics, tankers' prices and waiting times, household managers' knowledge of their households' water situation, prior experience with disruptions, and socioeconomic parameters affect the households' decisions when the piped IWS is disrupted.

3.1 Introduction

Households of IWS systems often adapt to the intermittency in water supply by storing water, obtaining water from other sources, and/or changing their water use patterns to adapt to the water supply (Majuru et al. 2016). Under normal operation conditions of the IWS system (i.e., static water supply durations and quantities), households' behaviors tend to be steady, and are governed

[4] Aljadhai, S. and Abraham, D. (2020). "Modeling Dynamic Consumer Decision during Disruptions of Intermittent Water Supply Systems." *World Environmental and Water Resources Congress 2020.* Henderson, NV. (pp. 360-373) ASCE (With permission from ASCE).

by their long-established adaption strategies. However, during disruption events, the variables that affect consumer decisions (e.g., non-piped water prices, availability, and quality) are more dynamic, and the household behavior is affected by the length and intensity of the disruption. Therefore, households may need to obtain water from sources that are different from, or at different prices and involving different waiting times, from what they are used to during normal operation of the IWS network. Investigating the variables that affect households' response to disruptions is important in understanding the demand for non-piped water sources for further analysis of the dynamics of the non-piped water market when responding to disruptions.

Prior research on analyzing households' choices of different sources of water supply focuses on two themes. Some prior studies analyzed households' choices of water sources to estimate household water demand in IWS systems. One approach for consumer demand estimation is using statistical analysis of historical data and/or survey observations to estimate the volume of household water use and analyzing the price elasticity of demand for a single source (Mimi and Smith 2000; Salman et al. 2008; Tabieh et al. 2012). In such studies, proxy indicators such as water price, household income, family size, house age, and weather have been used to build demand functions that explain residential consumption. Other studies used the same approach to estimate the consumer water demand from more than one source (for a detailed overview, see (Whittington and Nauges 2010)). These approaches focus on understanding the volumetric consumption and the price elasticity of demand rather than explaining the underlying consumer behaviors that drive their choices.

The second theme of prior research on analyzing consumer behavior focuses on explaining the consumer coping decisions considering alternative modes of water supply, conservation actions, and/or local storage. These studies analyze the consumer choice of water sources, the demand volume from each source, and/or cross-price and own-price elasticities of demand from different sources. Two-step statistical selection models (Acharya and Barbier 2002; Cheesman et al. 2008; Nauges and Van Den Berg 2009; Coulibaly et al. 2014) and cost-minimization optimization models (Rosenberg et al. 2007; Srinivasan et al. 2010a) are the main methods used to model the consumer choice of water sources. Acharya and Barbier (2002) used two-step Seemingly Unrelated Regression models to estimate the demand for water purchased from vendors and the water that is collected by households in rural regions of Nigeria. Cheesman et al. (2008) estimated the demand for municipal water and household well water in Vietnam. They used a Probit model to estimate the probability of having a household well and a Seemingly Unrelated Regression model to estimate the demand for both municipal and well water. Nauges and van den Berg (2009) used a selection model for the decision to connect to the piped network and then estimated the water demand from piped and non-piped (aggregated) sources in Sri Lanka. Coulibaly et al. (2014) developed a two-step model to estimate the consumer demand from four sources of water (piped system, water tankers, treated water purchased from small shops, and bottled water) in Zarqa, Jordan. The first step in their model determines the probability of using a water source (using a Probit model), and the second step determines the demand share of the source if chosen. These statistical models rely on observation data sets and/or surveys of consumer preferences to explain the consumer choice. The surveys in these studies are designed to (1) collect data about consumer behaviors during normal operation of the system (the system's steady-state) and, in some studies (e.g., Acharya and Barbier 2002; Cheesman et al. 2008) (2) collect information about households' revealed and stated preferences toward hypothetical scenarios of price changes. These models can assist in understanding consumer behavior during predictable normal operation scenarios but are not capable of explaining consumer behavior during unexpected system disruptions. In addition, these studies focus only on price elasticity of demand (i.e., how the demand would react to changes in prices) as an external variable to the consumer. Other external variables such as those related to water sources availability and reliability are not addressed.

Rosenberg et al. (2007) expanded the modeling of household water use in IWS systems by integrating multiple sources with different costs, availabilities, reliabilities, and qualities, and by including many conservation options as user actions. They used a stochastic optimization model that minimizes users' annual water management costs to estimate the household water use in Amman, Jordan, and to study the demand response to water pricing and conservation campaigns. In their model, households adopt long-term (i.e., irreversible) and short-term (i.e., reversible) supply enhancement and conservation actions in response to events of decreased quantities of available water from the source given probabilities of the event's occurrence. Although this work addresses a wide variety of short and long-term households' actions, the cost minimization model in Rosenberg et al. (2007) ignores households' heterogeneity in preferences (i.e., related to waiting times, the risk of running out of water, and inconvenience of obtaining non-piped sources), knowledge and awareness (of household water situation and/or non-piped sources), and prior experience with the IWS. In addition, their model does not explain the significant factors that drive households' decisions.

Prior research, except the work of Rosenberg et al 2007, focused on modeling households' behavior in IWS systems focused on households' long-term, static adaptations, assuming steady-state conditions of the water supply, and focused on modeling households' choices based on their history with the IWS system. In addition, less attention has been given to analyzing households' preferences about water conservation, waiting times, and inconvenience (due to affected water supply and/or related to obtaining non-piped water).

This study analyzes the short-term (i.e., temporary and dynamic) decision-making process of residential water consumers in a city in the Middle East that is supplied by an IWS system. Rather than focusing solely on consumer choice of alternate water sources, the study addresses other relevant decisions, including: (1) households' risk tolerance (related to the timing of their response to the disruption), (2) households' willingness to pay for the faster delivery of non-piped water supply, and (3) willingness of households' managers to pay to avoid the inconvenience of waiting in line to get water from a non-piped source. These three household decisions collectively (made by a large number of households) have an impact on the dynamics of the non-piped water market (e.g., prices, availability, and quality), which may in turn affect each consumer's decision. The study incorporates variables related to households' preferences, expectations, knowledge and awareness, and prior experience in addition to variables related to cost, housing characteristics, and socioeconomics that have been addressed in prior research. Variables related to households' previous decisions and experience with the IWS system are also analyzed. The hypotheses tested in this study are:

- When obtaining non-piped water during disruptions, households are heterogeneous in terms of their preferences regarding the risk of running out of water, their willingness to pay for faster delivery, and the willingness to pay for convenient non-piped sources.
- The knowledge and the awareness of the household manager about their water situation and their previous experience with the multi-mode water supply system have an impact on their preferences related to obtaining non-piped water.

3.2 Survey Design and Deployment

In IWS systems, the supply and consumption behavior of households is not easily readily discernible for many reasons. Utility billing information is less effective in understanding households' behavior since households are supplied with water from several sources. In addition, non-connected consumers and unmetered consumption are often present in IWS systems in developing countries.

Survey and observation methods have been widely used to understand and analyze households' water behavior in IWS systems (Whittington and Nauges 2010). A household survey was developed and deployed to understand the water management behavior of residential consumers in a city in the Middle East (described earlier in Section 1.8). Households in the city have adapted to the supply intermittency by installing/constructing in-house water storage tanks with various capacities and/or, in some cases, by supplying water from a utility-regulated market of water tanker trucks. However, during disruptions of the water network, the water stored in the household tank is often not sufficient to satisfy the household demand for the duration of the disruption, and households rely mainly on tanker trucks as an alternative mode of water supply. Typically, there are three types of water tankers in the city: free tankers provided by the utility, tankers at the regulated price (equivalent to $50), and tankers that are either unregulated or regulated but sell at unregulated (higher) prices. Households can get a water tanker by either placing a phone call, submitting an online request, using social media or by physically going to the tankers' location. Tanker locations (or tanker filling stations) are places where households can go and wait in-line to request a water tanker for immediate delivery.

In addition to increased supply from new desalination plants, the utility in the city has recently invested in network water storage that provides the capacity to transfer from IWS to continuous water supply (CWS) for many parts of the city. Nevertheless, the utility often switches the supply back to IWS in response to disruptions, especially during events that affect water quantities (particularly due to the disruption of sources).

The developed survey serves two functions. First, it assists in understanding the consumer's consumption and supply patterns during normal operation of the network to better gauge factors influencing the system under study (e.g., the volume of the private market, the intensity of disruptions, available actions for households, and factors affecting consumer's decision). Second, it extracts the consumer's stated and revealed preferences to be evaluated in modeling the consumer's decision. The survey collected data about: (1) the characteristics of the housing unit (to study their effect on consumer decision), (2) supply and consumption behavior during normal operation (to study the effect of consumer knowledge and previous experiences on their decision), (3) consumer supply and consumption behavior during disruptions (to reveal households' expectations and preferences), (4) consumer preferences such as willingness to pay, ability and willingness to conserve water, willingness to wait in line for free water, and (5) general socioeconomic information. The survey included two questions to filter the targeted respondents based on whether they live in the city and whether they are the managers of the household, and hence the decision-makers related to the household's water supply.

The estimated number of required responses is around 271 responses (assuming a 90% confidence level, 5% margin of error, and a sample size of 1.3 million households). Qualtrics, a web-based survey software, was used to format the survey and collect the responses. Internal validation of the survey has been done through reviews by subject-matter experts who have knowledge and experience with the water supply system and consumer behavior in the city. The survey was pre-deployed to household managers who have little knowledge about the IWS system to ensure that the survey was easy to understand by all classes of households and that they would be able to provide responses. The survey questionnaire was approved for exemption by the Institutional Review Board (IRB) of Purdue University with an IRB protocol number of 1810021257 (see Appendix B).

A total of 442 completed household responses were collected between February and March 2019. About 57% of the responses (251 responses) were for households living in single-family houses and having full control over their water supply and usage, while 43% (191 responses) were for households living in apartments where water storage is shared with other households. Respondents in the latter group do not have full control over the supply and/or consumption of the stored water in their building since the landlord of the building or a residents' association is usually in charge of supplying water to the building.

This study focuses on residents of single-family houses who have the capacity to make the decisions of interest. The responses were well distributed over different household sizes, income groups, and age, education level, and occupations of household managers. Table 3.1 shows the descriptive statistics of the relevant variables to the four dependent variables, all of which are indicator variables (i.e., zero or one). The results of the survey show that 85% of the respondents own their houses, while 15% are renters, living with family, or living in work-provided housing. In addition, 17% of the respondents receive continuous water supply for 24/7, 40% receive intermittent supply for 1 or 2 days a week, 14% receive between 3 to 4 days a week of intermittent supply, 10% think their supply mode is changing and has no apparent pattern, while 19% do not know what mode of supply they get in their houses. Most of the respondents (92%) live in houses with 4 or more bedrooms, while 42% of the households have more than 4 bathrooms that are used in a daily basis. 43% of household managers have had an experience of ordering a water tanker in the past three years, and 22% of households had to supply 3 tankers or more per year for the past three years. Regarding the knowledge and the awareness of the household manager about their household water situation, 78% of respondents know the size of their household's water storage tanks, and 20% of respondents indicated that they are likely to know about network supply shut-off since they regularly check their underground tanks.

A significant proportion (71%) of the respondents stated that they are likely to supply a water tanker even if they have water in their household storage (that can supply the regular household demand for two days or more) while the remaining 28% think they are likely to get a tanker only when they know that they will run out of water by the end of the day. Answering the question of the willingness to pay more for a faster delivery, 64% of the respondents are willing to pay twice the regular price of the water tanker in order to get the tanker on the same day or on the following day while 36% of respondents would rather wait two days or more before getting a water tanker at the regular price (equivalent to $50). When asked about their willingness to pay to avoid waiting in-line at the tankers' location, 56% of respondents stated that they are willing to pay the regular price of a water tanker and avoid waiting in-line for one to two hours for a free tanker. However, a lower percentage of respondents (48%) are still willing to pay as much as twice the regular price of a tanker in order to avoid a wait of more than three hours to get a free tanker.

Table 3.1. Descriptive statistics of exploratory variables related to households' decisions

Variable Description	Mean	Std. Dev.	Obs.
Variables related to ordering a water tanker early (Model-1)			
Indicator of willingness to pay twice the regulated price of the water tanker for a faster delivery (1 if yes, 0 if no)	0.637	0.482	251
Knowledge of water supply shut-off indicator (1 if household manager knows about supply shut-off, 0 otherwise)	0.203	0.403	246
Garden indicator (1 yes, 0 if no)	0.406	0.492	251
Higher tanker experience indicator (1 if greater than 2 tankers/year in the past three years, 0 otherwise)	0.221	0.416	244
House size indicator (1 if 4 bedrooms or greater, 0 otherwise)	0.916	0.277	251
Private employee indicator (1 if yes, 0 if no)	0.195	0.397	251
Maid of driver indicator (1 if household has a housemaid or a private driver, 0 otherwise)	0.789	0.409	251
Variables related to willingness to pay more for faster delivery (Model-2)			
House ownership indicator (1 if owner, 0 otherwise)	0.848	0.359	251
Retired indicator (1 if yes, 0 if no)	0.339	0.474	251
Water runout experience indicator (1 if 2 times or more in the past 3 years, 0 otherwise)	0.441	0.497	240
House size indicator (1 if 4 bedrooms or greater, 0 otherwise)	0.916	0.277	251
Higher water use for bathrooms indicator (1 if the house has greater than 4 bathrooms used on a daily basis, 0 otherwise)	0.418	0.494	251
Indicator for high monthly income with no preference of ordering tankers early (1 if greater than the equivalent of $4,000 and likely to order tankers only when running out of water, 0 otherwise)	0.198	0.399	251
Variables related to willingness to pay to avoid waiting in-line at the tankers' location (Model-3 and Model-4)			
High monthly income indicator (1 if greater than the equivalent of $5,300, 0 otherwise)	0.451	0.499	251
Knowledge about tank size indicator (1 if knows the tank size, 0 otherwise)	0.777	0.417	238
Less supply reliability opinion indicator (1 if less reliable, 0 otherwise)	0.275	0.448	251
Higher frequency of experience of going to the tankers' location (1 if greater than 50% of the times, 0 otherwise)	0.325	0.471	83
Thirties age category indicator (1 if 30-39 years old, 0 otherwise)	0.106	0.309	251
Planning of investing in household storage indicator (1 if yes, 0 if no)	0.333	0.472	251
House ownership indicator (1 if owner, 0 otherwise)	0.848	0.359	251
Intermittent supply indicator (1 if supply is for 1-2 days a week, 0 otherwise)	0.399	0.491	251
Children (1 if has children younger than 6-year old, 0 otherwise)	0.400	0.491	251
Greater than median monthly income indicator (1 if greater than the equivalent of $4,000, 0 otherwise)	0.676	0.469	251
Long-term actions consideration indicator (1 if considers a long-term action to manage water supply/consumption (except investing in water storage), 0 otherwise)	0.747	0.435	251

3.3 Methodological Approach

This research addresses three aspects of household decisions during disruptions; the timing of households' responses to the disruption (i.e., related to their preferences of the risk of running out of water), their willingness to pay for faster delivery of non-piped water, and their willingness to pay to avoid the hassle of waiting in-line for a non-piped water source. The responses of household managers to four questions with binary outcomes are analyzed and modeled in this study:

- Model-1 Are you likely to order a water tanker even if you have stored water in your household (that can supply more than two days of regular household demand)? (1 if yes, 0 if no)
- Model-2 Will you be willing to pay twice the regular price of a water tanker in order to get it faster (i.e., on the same day or the following day)? (1 if yes, 0 if no)
- Model-3 Will you be willing to pay the regular price of a water tanker to avoid waiting in-line for 1 to 2 hours for a free water tanker? (1 if yes, 0 if no)
- Model-4 Will you be willing to pay more than double the regular price of a water tanker to avoid waiting in-line for more than 3 hours for a free water tanker? (1 if yes, 0 if no)

Model-3 and Model-4 address the willingness of household managers to pay to avoid waiting in-line (at the tankers' location) at different prices and waiting times to evaluate the impact of longer waiting times on their responses.

Econometric and statistical methods are appropriate and commonly used for modeling household water management choices (Whittington and Nauges 2010). In this study, a set of four Binary Probit models are developed to statistically model these four responses since the responses are binary discrete variables, and the decisions are independent of each other. Binary probit models estimate the likelihood of a binary outcome occurring depending on the observable estimated parameters assuming normally distributed disturbances (Washington et al. 2010). For instance, Equation 3.1 estimates the probability of choosing to order a water tanker early (even if the household has a two-day supply of stored water) rather than waiting until running out of water (i.e., Model-1).

$$P_{order\_early\,,n} = \Phi\left(\frac{\beta_{order\_early\,,n}\, X_{order\_early\,,n}}{\sigma}\right) \qquad (3.1)$$

Where: $P_{order\_early\,,n}$ is the probability of a household manager (n) choosing to order a water tanker early, $\beta_{order\_early\,,n}$ is a vector of estimable parameters for the *order_early* outcome, $X_{order\_early\,,n}$ is a vector of the independent parameters related to the outcome, Φ is the standardized cumulative normal distribution, and σ is the variance (set to equal one).

The parameter vector (β) is estimated using maximum likelihood methods (Washington et al. 2010). Marginal effects are used to estimate the effect of the independent variable that is statistically significant on the probability of the occurrence of the outcome (Washington et al. 2010). To evaluate the overall statistical significance of the model, the likelihood ratio test is used, as shown in Equation 3.2.

$$\chi^2 = 2[LL(0) - LL(\beta)] \qquad (3.2)$$

Where $LL(0)$ is the log-likelihood at convergence of the restricted model (i.e., all parameters are set to zero except the constant), $LL(\beta)$ is the log-likelihood at convergence of the unrestricted model, and χ^2 is the chi-squared statistic with a degree of freedom equal to the difference between the number of the parameters of the restricted and the unrestricted models (Washington et al. 2010).

3.4 Estimation Results

Table 3.2 shows the estimation results, including the significant variables and their marginal effects on the likelihood of a household manager to supply a water tanker even if they have more than two-days of supply in their household storage tanks. Table 3.3 shows the estimation results for the decision to pay more to get the water tanker in the same day or the following day (rather than waiting for more than two days for a water tanker at the regular price). Table 3.4 and Table 3.5 provides the estimation results for the willingness to pay to avoid waiting in-line at the tankers' location. Table 3.4 shows the estimation results for the decision to pay the regular price of a tanker in order to avoid waiting for 1 to 2 hours in-line for a free tanker. Table 3.5 shows the results of the decision to pay twice the regular price of a tanker in order to avoid waiting for more than 3 hours in-line for a free tanker. All four models were found to be statically significant at 95% confidence level based on the examination of the chi-squared statistics. All independent variables in the models are statically significant at 99%, 95%, or 90% confidence levels.

Based on the results in Table 3.2 for the significant variables affecting the consumer's willingness to order a water tanker even before two days of running out of water (Model-1), consumers living in a larger house (4 bedrooms or greater) are more likely to avoid the risk of running out of water and order a water tanker early. In this study, running out of water is defined as having no water in the household storage tanks. The marginal effect of the house-size variable indicates that living in a larger house increases the likelihood of the consumer to order early by 0.25 (on average). The results also show that working in the private sector increases the consumer's likelihood to order the water tanker early by an average of 0.12. A possible explanation is that, in this city, private employees tend to be busier and work for longer hours than individuals in other job categories. Hence, they would prefer to avoid the wasted time and the inconvenience related to obtaining a water tanker. In addition, more than 70% of private-sector employees in the survey indicated that they regularly check their underground tanks and are more likely to know about supply shutdowns compared to a lower percentage of respondents who know about the supply shutdowns in other job categories (less than 50%).

The garden indicator and the maid-or-driver indicator in Table 3.2 can be seen as signs of household wealth, and they both have a negative impact on the likelihood of early ordering of a water tanker. Having a garden in the house decreases the probability of early ordering of water tankers by an average of 0.12 since households with gardens can conserve water if they stopped watering their gardens. In the survey, about 66% of households with gardens indicated that they would stop watering their gardens during disruptions in water supply. This effect of having a garden is in line with the findings of Coulibaly et al. (2014), who reported that households with a garden in the house have a lower consumption of water tankers. The likelihood of early-ordering of water tankers for households with a housemaid or a private driver (i.e., living in the house) is decreased by 0.19 on average. From the survey results, 80% of households with maids or drivers have a higher monthly income (more than the equivalent of $4,000), which suggests that even if they run out of water, they can afford getting a supply from water tankers in a relatively short time. Consumers who are willing to pay more (as much as twice the regular price) for faster delivery (i.e., on the same day or the day after) are less likely to order early, and their likelihood of ordering early is decreased by (0.12) on average.

The past experience of tanker orders (more than 2 tankers/year in the past three years) has a low positive effect on the likelihood of households' early-ordering by (0.0003), suggesting that the knowledge about the prices, the availability, and the waiting times of tankers leads households to order tankers early to avoid paying higher prices or experiencing longer waiting times. The effect of the personal experience of households on their perception of risk and on their averting actions has been reported in the literature of water supply. For instance, Nastiti et al. (2017) stated that personal experience of households is one of the factors that shape their perception of health risks and their averting actions related to water quality. Finally, consumers' knowledge about supply shutdowns to their houses shows an increase of (0.0003) in their likelihood of ordering early as they are more aware of their household's water situation and can take actions before running out of water.

Table 3.2. Binary probit model estimation results for Model-1 (ordering a water tanker early even if the household has a two-day supply of available stored water)

Variable Description	**Parameter Estimate**	**t-statistic**	**Marginal Effect**
Constant	0.872	2.61***	
Willingness to pay double the regulated price of the water tanker for faster delivery (1 if yes, 0 if no)	-0.417	-2.18**	-0.1253
Knowledge of water shut-off (1 if the household manager knows about supply shut-off, 0 otherwise)	0.001	2.00**	0.0003
Garden indicator (1 yes, 0 if no)	-0.390	-2.17**	-0.1230
Higher tanker experience indicator (1 if greater than 2 tankers/year in the past three years, 0 otherwise)	0.001	1.94*	0.0003
Private employee indicator (1 if yes, 0 if no)	0.413	1.77*	0.1190
House size indicator (1 if 4 bedrooms or greater, 0 otherwise)	0.741	2.30**	0.2514
Maid-or-driver indicator (1 if the household has a housemaid or a private driver, 0 otherwise)	-0.679	-2.62***	-0.1859
Number of observations		**252**	
Log-likelihood at zero, $LL(0)$		**-151.67**	
Log-likelihood at convergence, $LL(\beta)$		**-137.69**	
$\chi^2 = 2[LL(0) - LL(\beta)]$		**27.95**	

*****, **, *: Significance at 1%, 5%, 10% level**

Table 3.3. Binary probit model estimation results for Model-2 (willing to pay as much as twice the regular price of a water tanker to get the tanker on the same day or the following day)

Variable Description	**Parameter Estimate**	**t-statistic**	**Marginal Effect**
Constant	0.420	1.90*	
House ownership indicator (1 if owner, 0 otherwise)	-0.539	-2.19**	-0.174
Retired indicator (1 if yes, 0 if no)	0.456	2.46**	0.157
Higher water use for bathrooms indicator (1 if house has greater than 4 bathrooms used in a daily basis, 0 otherwise)	0.373	2.14**	0.130
Indicator for above-median monthly income with no preference of ordering tankers early (1 if greater than the equivalent of $4,000 and likely to order tankers only when running out of water, 0 otherwise)	0.539	2.43**	0.178
Number of observations		**252**	
Log-likelihood at zero, $LL(0)$		**-154.74**	
Log-likelihood at convergence, $LL(\beta)$		**-164.82**	
$\chi^2 = 2[LL(0) - LL(\beta)]$		**20.16**	

****, *: Significance at 5%, 10% level**

Table 3.4. Binary probit model estimation results for Model-3 (willingness to pay the regular price of a water tanker to avoid waiting in-line for 1 to 2 hours)

Variable Description	**Parameter Estimate**	**t-statistic**	**Marginal Effect**
Constant	0.633	1.92*	
House ownership indicator (1 if owner, 0 otherwise)	0.635	2.41**	0.2200
Intermittent supply indicator (1 if supply is for 1-2 days a week, 0 otherwise)	-0.376	-2.23**	-0.1287
Children (1 if there are children younger than 6-year old in the household, 0 otherwise)	-0.404	-2.19**	-0.1405
Lower than median monthly income indicator (1 if less than the equivalent of $4,000, 0 otherwise)	-0.560	-3.15***	-0.1918
Thirties age category (1 if 30-39 years old, 0 otherwise)	0.723	2.24**	0.2477
Planning of investing in household storage indicator (1 if yes, 0 if no)	0.319	1.67*	0.1093
Other long-term actions consideration indicator (1 if considers a long-term action to manage water supply/consumption, 0 otherwise)	-0.639	-2.99***	-0.2116
Higher frequency of experience of going to the tankers' location (1 if greater than 50% of the times, 0 otherwise)	0.0003	1.76*	0.0001
Number of observations		**252**	
Log-likelihood at zero, $LL(0)$		**-181.62**	
Log-likelihood at convergence, $LL(\beta)$		**-159.17**	
$\chi^2 = 2[LL(0) - LL(\beta)]$		**44.91**	

*****, **, *: Significance at 1%, 5%, 10% level**

Table 3.5. Binary probit model estimation results for Model-4 (willingness to pay double the regular price of a water tanker to avoid waiting in-line for more than 3 hours)

Variable Description	**Parameter Estimate**	**t-statistic**	**Marginal Effect**
Constant	-0.3759	-2.78***	
High monthly income indicator (1 if greater than the equivalent of $5,300, 0 otherwise)	0.7251	4.34***	.2594
Knowledge about tank size indicator (1 if knows the tank size, 0 otherwise)	0.0009	2.16**	0.0003
Less supply reliability opinion indicator (1 if less reliable, 0 otherwise)	-0.4021	-2.21**	-0.1432
Thirties age category indicator (1 if 30-39 years old, 0 otherwise)	0.5111	1.87*	0.1828
Planning of investing in household storage indicator (1 if yes, 0 if no)	0.3671	2.09**	0.1313
Number of observations		**252**	
Log-likelihood at zero, $LL(0)$		**-183.53**	
Log-likelihood at convergence, $LL(\beta)$		**-166.16**	
$\chi^2 = 2[LL(0) - LL(\beta)]$		**34.75**	

*****, **, *: Significance at 1%, 5%, 10% level**

Regarding the decision to pay twice the price of a regular tanker for same-day or following-day delivery (Model-2), the estimation results in Table 3.3 indicates that ownership of the house decreases the probability of choosing to pay more for faster tanker delivery by (0.17) on average. Households who own their houses are more likely to take long-term water management actions (such as investing in household storage or in water conservation devices) since they have full control over their houses, and hence they are more likely to be able to wait longer for a tanker delivery.

Being retired increases the consumer's likelihood of paying more for faster delivery by (0.16). Retired individuals are more affected by water supply disruptions since they are older and tend to stay home and are not as able to seek alternate water sources, as opposed to individuals who are still in the workforce. The results also show that a higher number of bathrooms that are used on a daily basis (greater than 4 bathrooms) increases the probability of the homeowner paying more for faster delivery (by an average of (0.13)). The number of bathrooms used on a daily basis reflects both the size of the dwelling and the size of the family. Finally, households with income above the median (the equivalent of $4,000) and also indicating that they would order tankers only when they run out of water, were found to be more likely to pay more for faster delivery. The marginal effect of this variable indicates that those households have an increase of (0.18) on average in the likelihood of paying more for faster tanker delivery.

The results in Table 3.4 and Table 3.5 that are related to the decision to pay to avoid waiting in-line at the tankers' location (Model-3 and Model-4) indicate that household income has an effect on the willingness of the household manager to pay to avoid waiting in-line. Having a high monthly income (greater than the equivalent of $5,300) increases the likelihood of choosing to pay twice the regular price for a water tanker (to avoid waiting in-line for more than 3 hours) by 0.26 on average. Similarly, having a monthly income lower than the median (less than the equivalent of $4,000) decreases the probability of choosing to pay the regular price of a water tanker (to avoid waiting for 1 to 2 hours in-line) by 0.19.

The results also show that two variables (age of household manager between 30-39 and the consideration of investing in household water storage) have positive effects on the willingness to pay to avoid waiting in-line for both situations. These effects suggest that younger household managers are less willing to accept the inconvenience of waiting in-line at the tankers' location. Additional examination of this variable could explain whether this effect (related to younger household managers) is due to their lack of experience, being busier in general, or due to other factors. Also, if household manager considers investing in household water storage, their likelihood of deciding to pay the regular price to avoid 1-2 hours of in-line waiting and the likelihood of deciding to pay twice the regular price to avoid 3 hours of in-line waiting are increased by an average of 0.11 and 0.13, respectively.

For Model-3 (willingness to pay the regular tanker price to avoid waiting in-line for 1-2 hours), the results in Table 3 shows that house ownership increases the likelihood to pay (by 0.22) to avoid waiting for 1-2 hours at the tankers' location, reflecting the fact that house owners have a higher disposable income in general compared to renters. The estimation results also show that having intermittent water supply (for 1-2 days a week) decreases the probability of paying for avoiding waiting in-line for 1-2 hours (by an average of 0.13). One possible explanation of this effect is that households with shorter supply durations are often supplied by free tankers by the utility, which may explain their unwillingness to pay for the water tanker. Having children under the age of six in the household causes a decrease (of 0.14) in the likelihood of paying to avoid 1-2 hours of waiting at the tankers' location. Similarly, if the consumer considers a long-term water management action (including installing water conservation devices, digging a well, or moving to another house), their probability of paying to avoid the 1-2 hours of waiting in line for water tankers decreases (by 0.21) on average. Finally, household managers who regularly go to the tankers' location to procure the water tanker are slightly more likely (by 0.0001) to pay to avoid the waiting time of 1-2 hours since they are used to an average waiting time of 30 minutes during normal situations (as stated in the survey responses).

For Model-4 (willingness to pay twice the regular tanker price to avoid waiting in-line for more than 3 hours), the results in Table 3.5 show that if the consumer considers water supply to their house as less reliable in the past three years (higher frequency of supply interruptions and/or longer durations of interruptions), their likelihood of paying to avoid waiting in-line for more than 3 hours decreases by an average of (0.14). Households with a higher frequency of disruptions are used to procuring water tankers at the regular price, which may explain their lower likelihood of paying double the price to avoid waiting in line. Finally, the results for Model-4 show that the consumer's knowledge about the size of their household storage tanks slightly increases (by 0.0003) their likelihood of being willing to pay twice the regular price of a water tanker to avoid more than 3 hours of waiting.

The results of the survey indicated that the number of household managers who are willing to pay to avoid waiting in line at the tankers' location decreases when the waiting times increase (assuming higher prices for avoiding long waiting times). By comparing the results of Model-3 and Model-4 in Table 3.4 and Table 3.5, it can be concluded that as the price to avoid waiting in line is double the regular price of a water tanker, the consumer's income becomes more relevant while the experience of going to the tankers' location becomes irrelevant. This finding suggests that households are more sensitive to the increase in the price of avoiding waiting in line for tankers rather than to the increase in waiting times at tanker locations. However, more analysis of different scenarios of increased prices and waiting times will be required to confirm this finding.

Although the analyzed decisions are theoretically independent (i.e., the choice of one decision does not directly depend on the choices in other decisions), the results show a partial effect of the willingness to pay for faster delivery on the likelihood of early-ordering of water tankers. This effect may be due to common unobserved data captured by the two choices in addition to the plausible logical effect explained earlier.

The results show that variables related to the household managers' previous experience and knowledge are also statically significant in modeling consumer decisions (including knowledge of tank size, awareness of water shutoffs, previous experience of ordering tankers, and previous experience of going to the tanker location). Despite the lower marginal effects of variables related to knowledge and prior experience, their inclusion in the models improved the overall model fit and improved the statistical significance of other variables.

Although using explicit variables instead of proxy variables may lead to a clearer interpretation of the results (e.g., replacing the maid-or-driver indicator by an income variable), the limited categories provided for the explicit variables in the survey might not be able to capture the effect of the variable on households' decisions. In addition, proxy variables can capture unobserved data (for example, having a housemaid or a private driver captures the household's income in addition to capturing some of their spending behaviors).

3.5 Verification and Validation

Verification and validation of the household decision-making models developed in this chapter include the validation of the household survey and the validation of the results with those of prior studies. The questions of the household survey were developed based on in-person interviews with utility personnel in July 2017. The different types of tanker options were determined based on these interviews, and the responses of households in the survey confirmed the types of tanker orders as the available options for households. The survey questionnaire was internally validated by reviews of six subject matter experts (SMEs) from the case study city, including university professors, utility engineers and managers, and water consultants with at least 8-year of experience with the system. The survey questions were discussed with the SMEs through in-person and phone interviews in December 2018 and in January 2019. The SMEs provided feedback regarding the sizes of tankers, sizes of household tanks, and the wording of some questions. The SMEs also suggested that the decision-making of households living in houses may be different from those living in apartments, which was considered in the modeling of household decision making. Two SMEs validated the Arabic translation of the survey questionnaire. The survey was externally validated by pre-deploying the survey to 15 household managers who have little knowledge about the IWS system to ensure that the survey was easy to understand by all classes of households and that they would be able to provide responses. Based on the external validation responses, some questions related to the household's prior experience of ordering tankers were edited and clarified. The responses collected during the external validation were excluded from the analyzed results.

The results of the survey showed well-distributed responses over different household sizes and income in addition to education level, age, and occupation of the household manager. The results of the survey were validated by two of the SMEs as reasonable and representative of the households' behavior of water supply and consumption in the city. The results of the survey showed a difference between households living in houses and those living in apartments similar to the findings of Coulibaly et al. (2014) where households who have their own water meters have a greater number of people, higher income, and more likely to have gardens than those who share a water meter. As indicated in the results of the household survey, households living in apartments mostly share the water meter with other households while households living in houses have their own water meters.

To validate the results of household decision-making models, the findings from relevant studies in the literature are compared to those of this study. Some of the variables that were found to be significant in the households' decisions were investigated in prior studies. Nauges and Strand (2007), Coulibaly et al. (2014), and Thneibat (2015) show a positive effect of household income on the consumption of water vended from tanker trucks, which supports the findings in this study that higher income increases the probability of paying for faster delivery of tanker trucks. In addition, Larson et al. (2006) found that higher income increases the probability of paying to avoid the inconvenience of collecting water from non-piped sources, reflecting the finding in this study of the effect of higher income on increasing the probability of paying to avoid the inconvenience of waiting in line at the tankers' location. These findings related to household income and wealth are in line with the economic theory that the demand for a commodity is affected by income, and was also found in the greater willingness to pay for improving piped water service for high-income households in IWS systems compared to low-income households (Asim and Lohano 2015)

Prior studies (Nauges and Strand 2007; Thneibat 2015) found positive effects of the dwelling/household size on demand for water tankers, suggesting that households with more members or larger houses are more willing to pay for improved water supply. Cook et al. (2016) reported that having a larger household increases the coping costs of poor piped-water supply associated with obtaining water from non-piped sources. These findings from the literature are similar to what was found in this study (for the variables related to the number of bedrooms and the number of bathrooms in the house).

3.6 Conclusions

This chapter analyzes the dynamic short-term behavior of households in IWS systems. The results of the econometric analysis of 252 responses to the household survey show that households in the analyzed IWS system are heterogeneous in terms of their preferences regarding obtaining non-piped water during disruptions. Households' decisions during network disruptions are affected by household characteristics (e.g., number of bedrooms, number of bathrooms, having children at home), wealth (e.g., income, ownership of the house, having a garden, having a housemaid or private driver), age and occupation (e.g., retired, private sector employee). In addition, the results show a statistical significance of variables related to households' previous experience with the system (including the experience of ordering tankers, the experience of going to tanker location, and intermittent vs. continuous supply). Some variables related to household managers' knowledge and awareness were found to be significant as well (knowledge about supply shutoffs, knowledge about tank size, and the consideration of future water management actions). These findings confirm the research hypotheses tested in this chapter.

One of the main contributions of this study to the body of knowledge is that, rather than simply modeling households' choices of different water sources, the study addresses the dynamics in households' responses to disruptions that have an effect on the prices, availabilities and waiting times of non-piped water sources. These analyzed dynamic decisions address households' preferences about water conservation, waiting times, and inconvenience associated with obtaining non-piped sources. In addition, this study expands the evaluation of households' short-term decisions to address the heterogeneity in households' knowledge and prior experience.

The results of this study can assist the city's water managers in estimating the changes in the demand for each type of non-piped water source when the system is disrupted. In addition, the results can assist water managers in the city in regulating, coordinating, and utilizing the market of water tankers. For example, increasing the number of tankers' locations would not only decrease the waiting times but also would lead to more household managers willing to pay to avoid waiting (as the price for avoiding waiting decreases), which also decreases the waiting time at tankers' locations.

This study has some limitations. First, the survey data was collected in a specific geographic location. Households' opinions and preferences are shaped by the current and the past conditions of the water supply system in this particular city. Data from other cities (even with similar system configurations) might result in different variables of significance that affect households' decisions. Second, the analysis and the findings of this study are limited to households living in houses. The results of the study suggest that the water supply and consumption behavior of households living in apartments are different from the behavior of residents of houses. Models that explain the behavior of apartment households were tested based on the survey responses, but the results were not conclusive. This suggests that additional data specific to apartment households (e.g., related to the management of supply and demand in apartment buildings, the inclusion of bottled water as an alternative supply, consideration of temporary moving) will be required to develop models specific to this class of households.

4. ANALYSIS OF THE DYNAMICS OF STAKEHOLDERS DURING DISRUPTIONS OF INTERMITTENT WATER SUPPLY SYSTEMS

This chapter analyzes the dynamics of the stakeholders in IWS systems in response to disruptions of the piped water distribution network (WDN), as well as the impact of these dynamics on the community resilience at the household level. While the resilience assessment framework presented in Chapter 2 considers the piped network as the only water supply available to households, this chapter investigates the impact of additional non-piped sources on the households' ability to maintain water supply. The stakeholders of the IWS system identified in this study are the households, the water utility, and the entities in the private market of non-piped water. Physical disruptions to the WDN have multiple effects on the stakeholders of the IWS system. Household consumers may experience various levels of water shortages, depending on their households' consumption, supply, and storage attributes. The water utility may take temporary measures to improve, coordinate, manage, and/or control the non-piped sources of water supply (e.g., water tankers) for the benefit of affected consumers. Disruptions to the piped system also have an effect on the market for other sources of water supply due to changes in demand and changes in prices and availabilities.

The two main hypotheses tested in this chapter are:

- The behavior of stakeholders is affected by the dynamics of the WDN where the network supply to consumers changes throughout the duration of the disruption.
- The dynamic interactions between stakeholders during system disruptions may result in emergent behavior in the system. Emergent behavior can be defined as the complex outcomes as a result of the collective effect of simple rules.

The behavior of the stakeholders in response to disruptions is modeled using Agent-Based Modeling (ABM) that also integrates the dynamics of the WDN during disruptions. The model is implemented and evaluated using a case study of the IWS system in the city in the Middle East, described in Section 1.7. The primary output of the model is the average duration during which households had no water in their household storage. The emergent behavior of interest is the change in the distribution of the demand for different types of water tankers in the city during the disruption of the WDN and the ability of the tanker market to fulfill the demand.

4.1 Literature Review

This section provides a discussion of the prior studies on analyzing the *coupling* of components of IWS systems. The focus of this literature review is on prior studies that address the *interactions* between the system's stakeholders to identify the current research gaps.

4.1.1 Prior Studies on Analyzing the Interactions between the Components of IWS Systems

A significant portion of the prior research on the analysis of IWS systems narrowly addresses one of the four main components of the IWS system (namely, WDN, households, the utility, and the private market of non-piped water). Reviews of the literature focusing on the WDN and on the households were provided in Chapter 2 and Chapter 3, respectively. Regarding the private market of non-piped water, prior studies focused mainly on the estimation of the households' demand for water tankers.

Fewer studies analyzed the coupling of two or more of these components, where the *interactions* between the coupled components are captured and addressed. Table 4.1 summarizes the context, tools used, contribution, and shortcomings of the prior work that analyzed the dynamics of the interactions between two or more of the IWS system components.

Urban water management approaches are largely based on a utility-centric view of the urban water supply system (Srinivasan et al. 2010b). On the other hand, the demand-side analysis takes a decentralized approach, which better explains the consumers' behavior in an IWS system, where consumers regularly rely on sources of water supply that are not provided by the utility. However, analyzing these approaches in isolation from each other fails to capture or explain the inter-component interactions within the water supply system. Analyzing IWS systems requires an integrated system approach that has the capacity to explain the effect of the dynamics of subsystems on each other and on the system as a whole. Few research studies in the literature have adopted an integrated analysis of the IWS systems.

Table 4.1. Prior Research on the Coupling of IWS System Components

Study **IWS system Components**	**Context**	**Research tool(s)**	**Main contribution(s)**	**Shortcomings**
Rosenberg et al. (2007) • Consumers • Water manager	Estimation of household water use Long-term analysis	Stochastic optimization of user actions (minimize user's annual water management cost)	- Integration of multiple sources with different costs, availabilities, reliabilities, and qualities - Inclusion of many conversation options as user actions	- Utility actions are limited to water pricing and conservation campaigns - The effects of consumer's decision on the water system are not addressed
Srinivasan et al. (2010a) • Consumers • Water manager • Non-piped private market	System analysis of urban water supply Long-term analysis	Hydrologic-economic model Five system modules	- Analyzing the interactions between the consumers and the water resources	- Water distribution by the piped network is analyzed without actual simulation of water hydraulics - Analysis of *one-way* interaction between the water manager and the consumers
Klassert et al. (2015) • Consumers • Water manager	Analysis of the distribution of the burden imposed by piped-water pricing policies Long-term analysis	Agent Based Modeling of households	- Analyzing the socio-economic heterogeneity of household consumers	- Static tanker market - Low-resolution estimation of water distribution by the piped network (assumes equal water supply distribution among households)
Thneibat, (2016)	Analysis of interactions between different water sources with efforts of water conservation Long-term analysis	System Dynamics	- Assessing the impact of the private tanker market on the efforts of water conservation - Addressing the dynamics in the tanker market	- Assumes static piped supply - Does not consider disruptions to the piped network

To the knowledge of the author, the work of Srinivasan et al. (2010b; a) is the only analysis that used a system modeling approach to study the dynamics of IWS systems. Srinivasan et al. (2010a) developed a system-approach hydro-economic model to analyze the dynamics of the urban water supply system in Chennai, India. Five sub-systems were modeled (four water resources, namely, reservoir, groundwater, water utility, and tanker market, and the consumers). A modular-simulation approach was used to model these sub-systems and link them with feedback channels. In doing so, the authors were able to integrate and calibrate modules with different temporal and spatial scales in one interconnected system.

The focus of Srinivasan et al. (2010b) was on the interaction between the supply and demand of the system. They analyzed how consumption behavior of the consumers affects the water resources (the reservoir and the groundwater) and vice-versa. The primary goal of the water utility module in this study was to calculate the share of the supply extracted from each water resource. The utility model used a Hierarchical Distribution Algorithm to distribute the available supply to different consumer categories, considering only the duration of the supply and the network shutdown. However, other dynamics and issues of the piped system (such as physical disruptions, pressure fluctuations, supply inequity, and others) that determine the quantities of water delivered to customers were not included.

4.1.2 Gaps in the Literature of the Analysis of IWS

The main gap in the literature of IWS systems is the lack of research work that addresses the *dynamic* coupling between all IWS system components. During a physical disruption of the piped network, the four system components (namely, the piped network, households, vendors of non-piped water, and the utility) show an interconnected dynamic behavior especially when consumers rely greatly on intermittent piped water supply.

In particular, the analysis of the interactions between the dynamics of the *piped system (WDN)* and the dynamics of stakeholders is missing in prior research. The prior studies that analyzed the dynamics of the piped system assumed static inputs regarding consumer demand and utility policy. On the other hand, the studies that analyzed the dynamics of the stakeholders assume static characteristics of the piped system. When analyzing the response of the IWS system to physical disruptions, the dynamics of the piped system play a significant role in the behavior of stakeholder and vice versa. For instance, the recovery process of the piped network will greatly affect the short-term demand of the tanker market. However, due to the lack of short-term *resilience* analysis (i.e., analysis of the IWS system's response to physical disruptive events), the literature in IWS systems appears to ignore these interactions to simplify the process of water distribution by the piped network. Furthermore, abstracting the piped network model might be intentional (for instance, in the case of ABM development of the consumer decision), and simple assumptions are used instead to limit the source of complexity in the system to the *interactions* between the components in order to have a clearer interpretation of the results (Klassert et al. 2015b). This strategy can be justified when the piped network tends to have static behavior. However, in situations where the behavior of the piped network is dynamic (due to disruptions), the network should be modeled in sufficient depth to track and study stakeholders' reactions to such disruptions.

4.2 Methodology

The proposed modeling approach (Figure 4.1) captures the dynamics of the four components of the IWS system and their interactions. The dynamics of the physical WDN are analyzed using the WDN Resilience Assessment Model (discussed in Chapter 2) to determine the impact of physical disruptions on household consumers and assess the impact of utility response on the recovery of the physical network.

The interactions between stakeholders in the IWS system when responding to network disruptions are modeled using Agent-Based Modeling (ABM). Households are modeled as autonomous agents who react to the disruptions of network supply by supplying water from different non-piped sources with different prices and waiting times. ABM, as a micro-modeling approach, is appropriate to model the dynamic decisions of household consumers in IWS systems and captures the heterogeneity in their water demand, storage capacity, risk taking, ability and willingness to conserve water, and willingness to pay for non-piped water sources.

In general, households in IWS systems have four categories of non-piped water sources that may be available:

- Private household wells

- Public (mainly free) water access points that involve waiting in lines and/or traveling time, cost, and/or inconvenience
- Water tanker trucks private vendors
- Bottled water

These different types of non-piped sources have different availability, water quality, price, convenience, and waiting times. The preferences of the household consumers that determine their decisions are based on empirical data from a household survey (described in Chapter 3).

Entities in the market of non-piped water are modeled as another class of agents who react to the changes in the demand by changing the prices. The behavior of the water manager (e.g., utility) is implicitly captured by the static parameters that represent the policies of the water manager during network disruptions (policies for both the household consumers and the market of non-piped water). An example of the policies related to households is that, in some IWS systems, the water manager may provide consumers with free non-piped water during disruptions. An example of the policies for the market for non-piped water is that the water manager may have the capacity to control the prices, the sources, and/or the quality of water in the non-piped market. The policies of the water manager/utility are assumed to be long-term, and they do not change within the short-term analysis of stakeholders' behavior during a disruption. The dynamic interaction between stakeholders of the IWS system (i.e., household consumers and the non-piped market entities) occurs at the ABM-environment level, which contains the variables that get updated based on the decisions of stakeholders.

The WDN resilience assessment model is integrated into the ABM model by two parameters that determine the number of affected households and the duration of the household-supply disruption. This simplification in representing the impacts of the disruption on households limits the complexity in the model to the interactions between agents (as suggested by Klassert et al. (2015)), while preserving the dynamics of the WDN during the disruption.

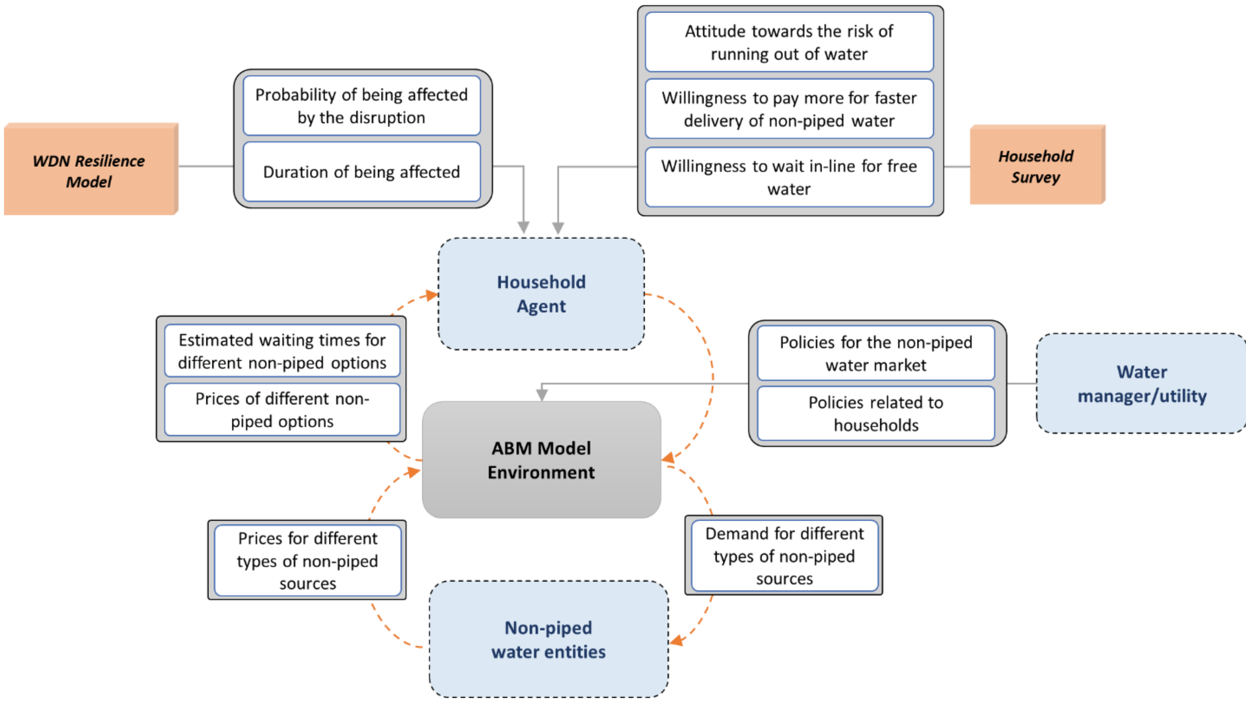


Figure 4.1. Schematic modeling of the dynamics of stakeholders in IWS systems during network disruptions

4.2.1 Model Implementation

The proposed model was implemented in the context of the IWS system of a city in the Middle East (described earlier in Section 1.7). The implemented model demonstrates the viability of the integrated WDN Resilience-ABM modeling approach in evaluating the interdependencies and dynamics of the components of the IWS system.

4.2.1.1 Description of the IWS System of the Case Study City

The IWS system in the case study city consists of four components: the physical intermittent WDN, household consumers, the water utility, and the private water tankers vendors. The water utility in the city is a government-owned corporation that owns, manages, and operates the WDN. The water utility, with the authority provided by the Ministry of Water, controls and operates the water tankers market. The fragmented tankers market consists of individuals or small firms who own the tanker trucks and get their water mainly from utility-controlled tanker filling stations at a fixed price that is set by the utility. The filling stations supply water either from the WDN or from utility-owned wells. A smaller portion of these tankers supply water from privately-owned wells that are licensed by the utility. Utility-independent private water companies who have their own tanker trucks and have their own licensed water sources, constitute another class of tankers. The size of all types of tankers (those controlled from the utility and those controlled by independent companies) ranges between 8 to 32 m^3 with the most common size of 24 m^3.

For utility-controlled tankers (who are served at the filling stations owned by the utility), the utility sets a fixed selling price for the unit volume of water provided by tankers to households based on the highest rate in the utility's water block-rating structure (equivalent to $1.8/$m^3$). However, during disruptions of the network supply that result in longer waiting times at the filling stations, utility-controlled tankers may increase prices due to the lack of enforcement of the price policy since the utility relies on consumers (who are not always aware of the prices) to report tankers' pricing violations. The utility pricing policy does not apply to utility-independent tanker companies, and their price follows supply-demand relationships. During normal operational conditions (where there are no disruptions to the WDN), the utility-independent tankers mainly supply water to commercial and industrial consumers, but they may supply to households when prices increase during disruptions.

The preferences of household consumers in the city are obtained from the results of a survey of 440 households (the total of those living in houses and in apartments). As discussed earlier in Chapter 3, households obtain water tankers either by waiting in person at the tankers' filling station (for free most of the time), by ordering a tanker at the regular price (i.e., utility-regulated price) or by ordering a tanker at a price higher than the regular prices.

4.2.1.2 Description of the Integrated ABM Model

The modeling approach described in Figure 4.1 was applied to the IWS system in the case study city. The developed ABM model addresses the dynamics and interactions between the four components of the IWS system. The ABM includes the household consumer and the water tanker as the two main agent classes. Figure 4.2 describes the structure of the ABM and its integration with the other components of the IWS system (i.e., the WDN and the water manager/utility). Figure 4.2 also includes the beliefs, knowledge, and information (BKI) diagrams for the household and the water tanker agents. The model was implemented in AnyLogic 7.1.

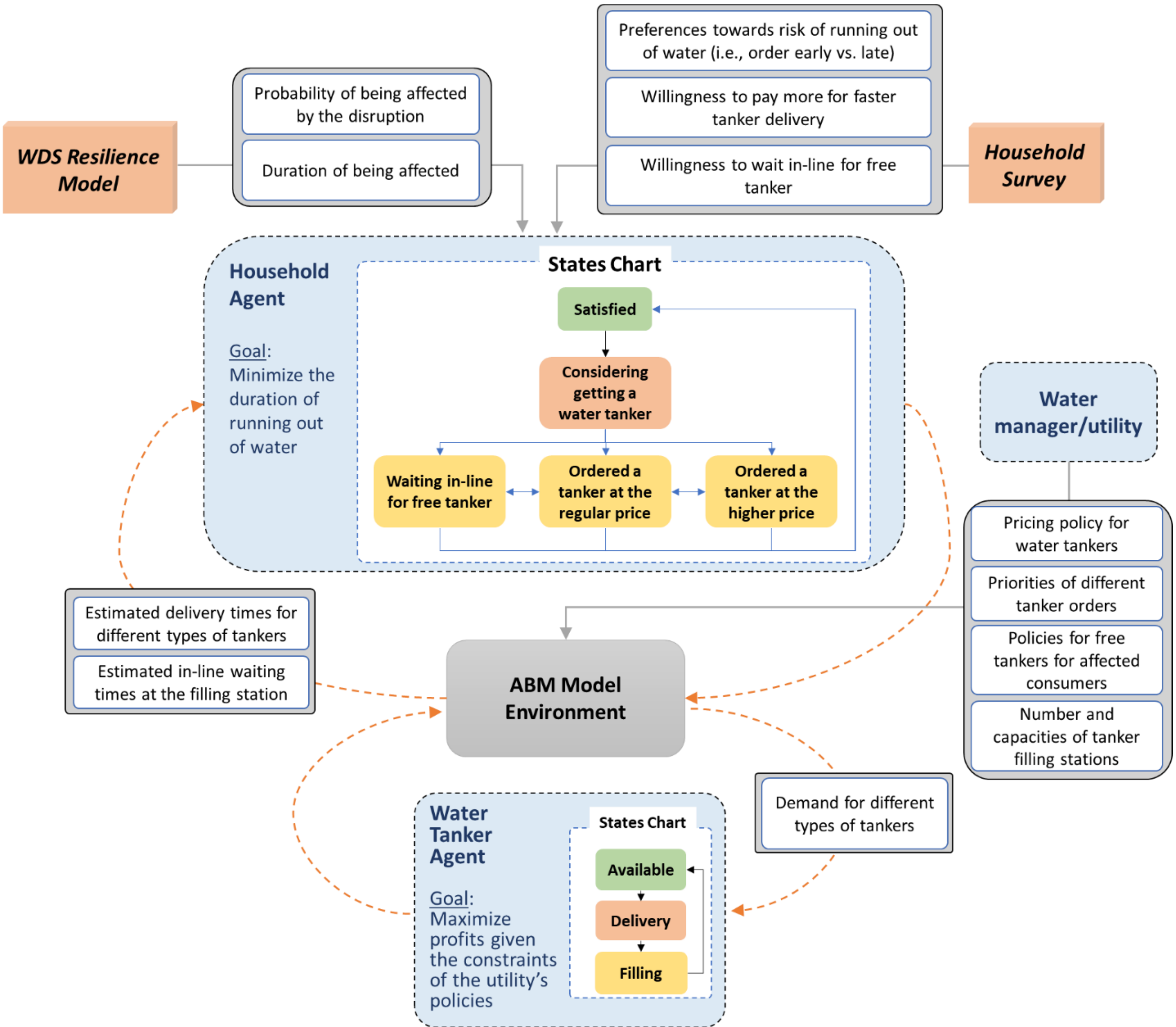


Figure 4.2. Structure of the ABM including the BKIs of the Household Agent and the Tanker Agent

The household agent represents household managers who try to manage their water consumption and/or demand to avoid or minimize the time of running out of water (where they have no water in their household storage tanks). At the beginning of the simulation, all household agents start at the state where their demand is completely satisfied. Household agents move to the state of "considering a water tanker" based on the probability of being affected by the disruption (estimated by the WDN resilience model). Affected households do not consider getting a water tanker until two days before their household tanks runout (as observed in the household survey). Figure 4.3 explains the decision-making process employed by household agents when choosing between different types of water tankers. Based on their risk taking/aversion preferences, household agents either order a water tanker early or wait until they have completely run out of water. Household agents observe information from the ABM environment related to the available options of water tankers and their associated waiting times to make decisions based on their preferences of willingness to wait in person at the filling station and/or willingness to pay for faster tanker delivery. In this study, it was assumed that household agents consider tankers of higher prices *only* if the estimated delivery time for regular-price tankers exceeds 24 hours. The price of the higher-price tankers is assumed to be equal to the double of the regular price that is set by the utility since the results of the survey indicate that the household's decision is only sensitive to prices that are double the regular price or greater. Household agents are allowed to change their decisions as they constantly update the information about the available tanker types and their waiting times.

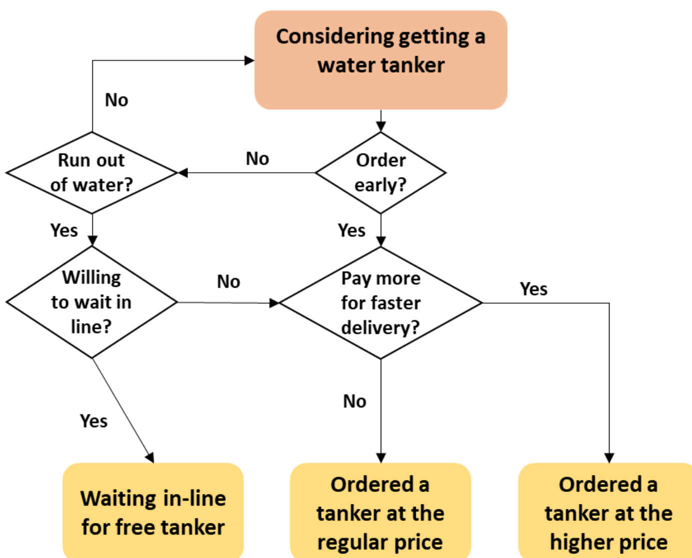


Figure 4.3. Decision-making structure for the household agent

The tanker agent represents tanker truck owners who try to maximize their profits by supplying water to as many households as possible and by increasing the prices of tankers if households are willing to pay. There are two types of tanker agents: one represents the utility-controlled tankers and the other represents the tankers of utility-independent tanker companies. The main difference between the two types of tanker agents is that utility-independent tankers supply to households only when prices are higher than the regulated tanker price (i.e., when requests of higher-price tankers are created by households). When a household agent decides to get a water tanker of a specific type, they create a tanker request that is stored in a waitlist in the model environment. Utility-regulated tanker agents choose tanker requests from the three waitlists (one waitlist for each tanker type) on a first-come-first-served basis. Tanker agents give priority to the requests of higher price tankers in order to maximize their earnings. When a tanker chooses a request, they move from the "available" state to the "delivery" state to represent the time required for the traveling trip and the filling time of household storage tanks (assuming a uniform distribution between 2 to 4 hours for the tanker delivery). Based on the sizes of household tanks in the case study city, tankers are assumed to fill only one household tank per trip. When a tanker completes the request of a household, they send a message to the household agent to move to the state "satisfied", and the tanker agent moves to the state "filling" which simulates the process of filling utility-controlled tankers at filling stations. The process of filling tankers is determined by the capacity of the filling station (number of tankers per hour) that depends on the number and the capacity of filling stations provided by the utility.

The behavior of the utility is limited to the parameters that describe the utility policies related to the households and to the tanker market. One policy related to households is that the utility in the case study city provides free tankers at the filling station for households who run out of water. For the tanker market, utility-controlled tankers are required by the utility policy to give priority to free-tanker requests for household consumers waiting at the filling stations(s). The behavior of the utility is assumed static during the short-term analysis (2-3 weeks).

4.3 Results and Discussion

The dynamics of the stakeholders in the IWS in the case study city were evaluated using the developed ABM. The analysis is based on the behavior of households within a representative sub-network of the city's WDN (described in Section 1.7) using the city-scale distributions of household attributes obtained from the household survey. Table 4.2 describes the values and the justifications for the model's parameters for the IWS in the city. The stakeholder's dynamics are evaluated by running the ABM model in AnyLogic for different combinations of WDN disruption scenarios (Figure 2-18). For each WDN disruption combination, the household's probability of being affected (i.e., percentage of affected consumers) and their average length of network-supply disruption are estimated from the WDN resilience model and used as inputs for the ABM.

The main evaluated output of the ABM model is the average household's water runout duration, which is the duration between the time when the household runs out of water until the time where water was supplied to the household either by a water tanker or by the return of the network supply. The average household's water runout duration is an indication of the overall performance (in terms of household demand satisfaction) of the IWS system, including the water tanker market. The evaluated outputs also include the number of completed orders of each tanker type in addition to the number of incomplete orders. The number of completed orders of each tanker type shows the distribution of the cost burden of the recovery of the system among households and the utility. Incomplete orders represent tanker orders that were generated by households; however, the network supply returned to the household before the order was chosen or completed by the tanker agent. The higher the number of incomplete orders indicates the higher intensity of the disruption and/or the shorter duration of the impact, while lower values of incomplete orders indicate lower intensity and/or longer duration of impact. Incomplete orders are not used to evaluate the capacity of the tanker market in fulfilling the households' demands because each combination run has a different time of network supply recovery that terminates the simulation. Incomplete orders are presented to reflect the total number of generated tanker orders. Another evaluated output of ABM is the average waiting time for completed orders, which reflects the supply-demand gap of the tanker marke

Table 4.2. Parameters for the evaluated IWS system in the case study city

Parameter type	Parameter	Value (unit)	Source/rationale
Parameters of the disruption of the WDN given a disruption scenario (type and intensity)	Household's probability of being affected	Variable	IWDN Resilience assessment model
	Length of the disruption of WDN supply to households (mean)	Normal distribution (hours) Variable	IWDN Resilience assessment model
IWS system parameters	Households' probability of vending water *early* by tanker truck (i.e., consumer's risk aversion attitude)	0.71	Household survey
	Probability of the willingness of the household manager to pay more for faster delivery (arrives the same day)	0.64	Household survey
	Probability of the willingness of household manager to wait in line (for more than 1 hour) to obtain a free tanker	0.44	Household survey
	Maximum waiting time before willing to pay high for faster delivery	24 (hours)	Household survey
	Number of households	2000 (0.1% of population)	Number of house connections in the analyzed sub-network
	Number of utility-regulated tankers	15 (133 consumers/tanker)	Proportional number of tankers for the analyzed sub-network
	Number of utility-independent tankers	5 (33% of number of utility-regulated tankers)	Proportional number of tankers for the analyzed sub-network
	Capacity of filling station	4 (tankers/hour)	Proportional capacity of filling stations for the analyzed sub-network
	Tankers delivery trip (including the trip to the consumer and filling household tank)	Uniform distribution (2-4) (hours)	Estimated by the utility (based on interviews with utility personnel)

The results of all combinations of *household tank capacity* and *recovery resources* for the pipe-damage disruption scenario are shown in Figure 4.4. For the source-disruption scenario, Figure 4.5 shows the results of all combinations of *household tank capacity* and the *length of the source disruption.* Figure 4.4 and Figure 4.5 show the household dynamics (the change in the number of households waiting for each type of tanker orders) over time. The curves in the figures show similar patterns that scale with the changes in the intensity and the duration of the disruption. The number of households ordering different types of tankers deceases as households switch to another order type, receive water supply through a tanker, or network supply is restored to the household. The sharp decline in the number of households ordering regular-price tankers reflects the behavior of households switching to either free or high-price tanker types when households run out of water.

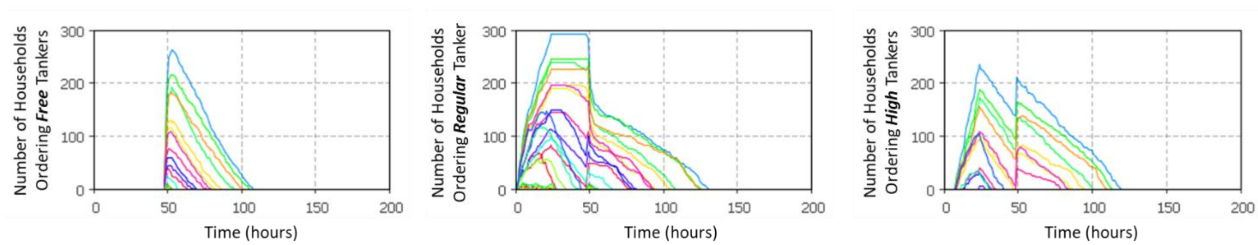


Figure 4.4 Household dynamics over time for all combinations of the pipe-damage disruption scenario showing the change in the number of households waiting for different types of tanker orders

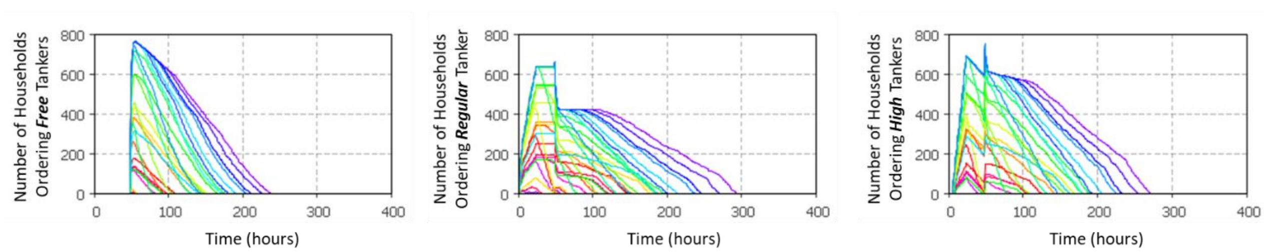


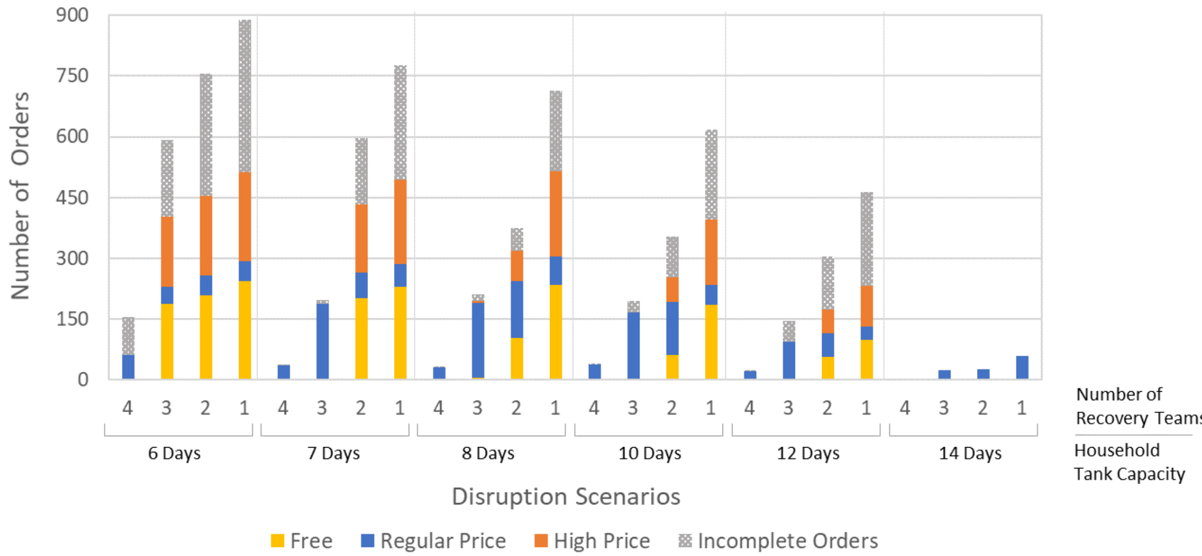
Figure 4.5. Household dynamics over time for all combinations of the source-disruption scenario showing the change in the number of households waiting for different types of tanker orders

To assess the impact of the interactions between stakeholders on the performance of the IWS system, Figure 4.6 summarizes the results of all combinations for the pipe damage disruption scenario. The top part of Figure 4.6 shows the total number of different types of tanker orders generated by households for each combination run. The bottom part of Figure 4.6 shows the resulted average water runout duration for households and the average waiting time for completed orders in addition to the attributes of the WDN disruption (the percentage of affected households and the average household's network-supply disruption). A similar set of results is provided for different combinations of household tank capacities and source disruption duration for the *source-disruption scenario* in Figure 4.7.

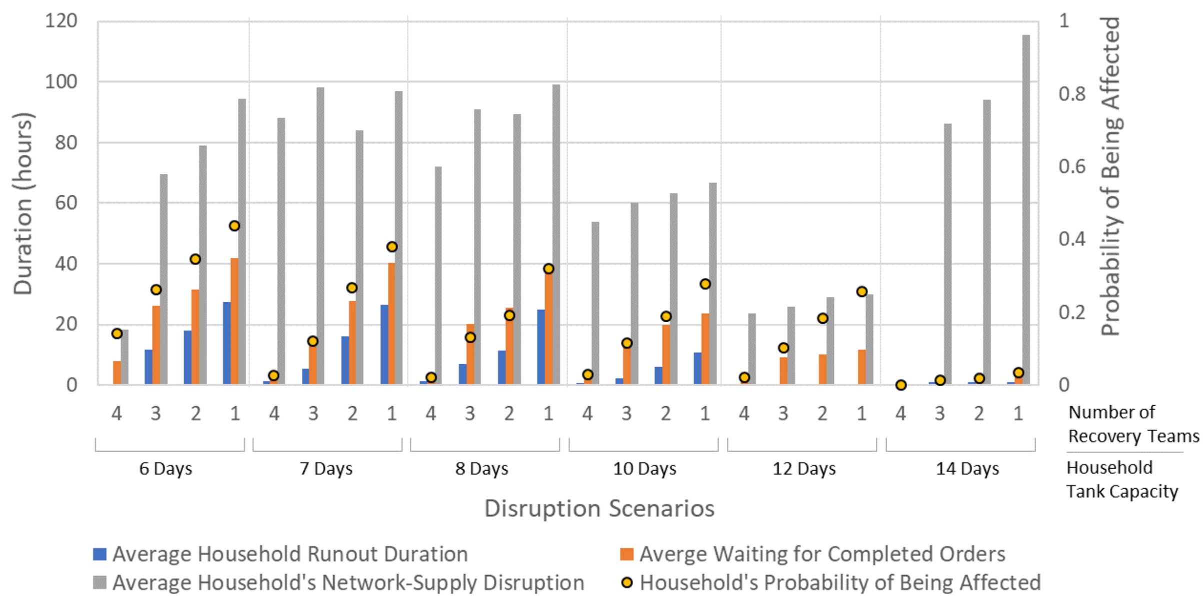
The resulting number of generated tanker orders is linked directly to the percentage of affected households. However, the variation in the distribution of different types of *completed* orders represents the impact of the interactions between the households and the tanker market. The number of completed orders of high-price tankers (in general) is correlated with the average waiting for completed orders (orange bars in the bottom part of Figure 4.6 and Figure 4.7) because orders for high-price tankers emerge during the simulation when estimated waiting times of new orders exceeds 24 hours. The number of free tanker orders is positively correlated with the average household runout duration (Figure 4.6), reflecting the effect of utility policy. However, the change in the number of completed free tanker orders in Figure 4.7 is a result of the interdependency between the demand of different types of tankers being intensified with a greater number of affected consumers and longer durations of households' network-supply disruption. The results show that, as the disruption's intensity increases, households tend to move to either to high-price or free tanker options over the regular-price tankers as an emergent households' response to the tankers' behavior of favoring these two types of orders. It was observed that this behavior of households emerges when the household's probability of being affected exceeds 20%, after which the tanker market becomes overwhelmed. This finding suggests that the utility should target a recovery process of the disrupted WDN that minimized the number of affected households even if it results in longer durations of households' network-supply disruptions. The results of the household survey indicated that regular-price tankers constitute the majority of the demand in the tanker market in the case study city during the period of 2016-2019. During this period, disruptions of the WDN were limited and isolated, resulting in less than 10% of affected households. However, the results in this analysis reveal that, if the city experiences more intense disruptions (>20% affected households), the tanker market will mostly operate on free and high-price types of orders. This behavior of the tanker market indicates longer waiting times for completing orders and longer water runout durations of households.

The difference between the resulted average household runout duration and the average household network-supply disruption (orange and grey bars in the bottom of Figure 4.6 and Figure 4.7) shows the positive effect of the tanker market in reducing the impact of the WDN disruption (taking into account the percentage of affected households). The results show that the tanker market always improves the demand satisfaction for the affected households, and affected households may never experience water runout in some cases where the capacity of the tanker market is able to fulfill the household demand in a timely manner.

The results in Figure 4.6 and Figure 4.7 show that both the *number* of affected households and the *length* of being affected have an impact on determining the effectiveness of the tanker market in minimizing the consequences of the disruption of the WDN. A larger number of affected households results in longer waiting times, which increases the demand for high-price tankers and the ability of the tanker market to fulfill the household supply. However, the ultimate effect of the disruption on households in terms of the duration of running out of water is also determined by the length of the household's network-supply disruption.

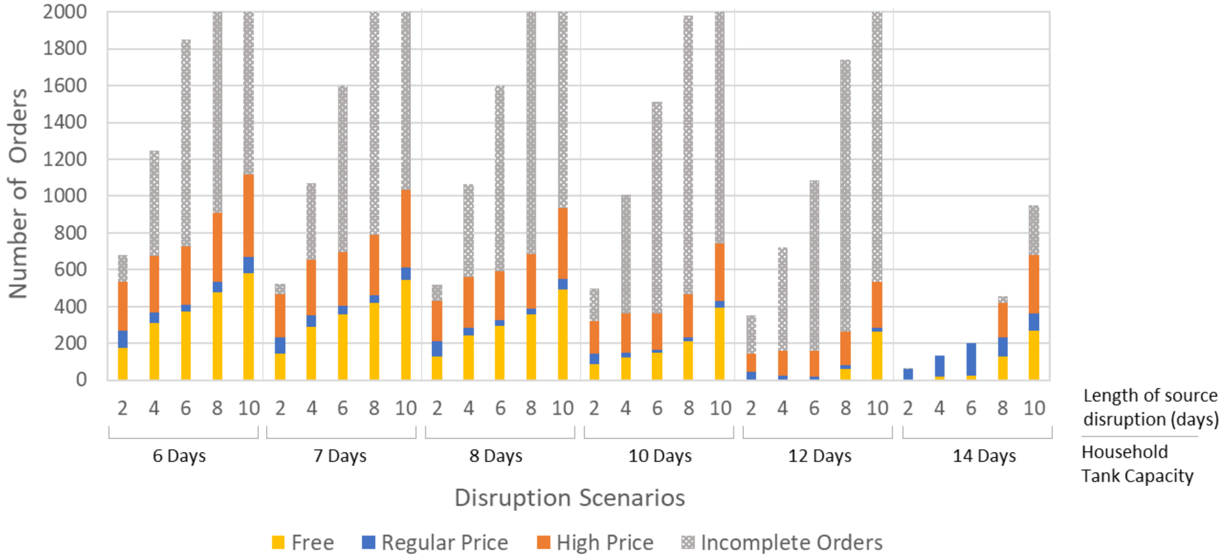


(a)

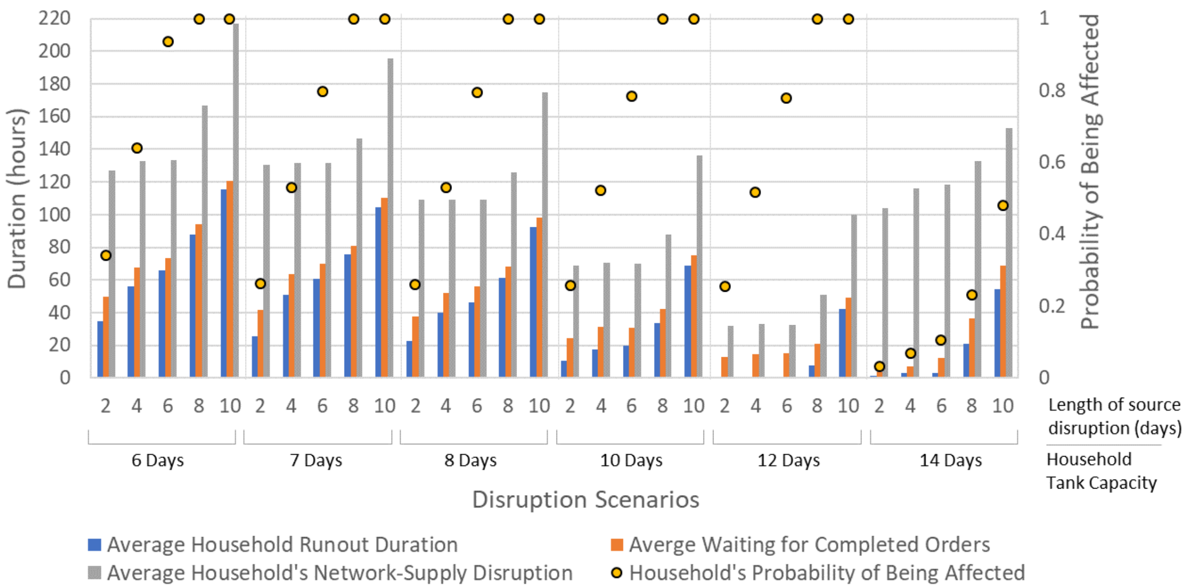


(b)

Figure 4.6. Results of the ABM for different combinations of the *pipe-damage* disruptions of the WDN, including (a) number of different types of tanker orders, and (b) average household's runout durations, average waiting for completed orders, and the attributes of the disruption of the WDN (household's probability of being affected and the average length of the disruption of the household's network-supply)



(a)



(b)

Figure 4.7. Results of the ABM for different combinations of the *source-disruption* scenarios of the WDN including (a) number of different types of tanker orders, and (b) average household's runout durations, average waiting for completed orders, and the attributes of the disruption of the WDN (household's probability of being affected and the average length of the disruption of the household's network-supply)

4.3.1 Analysis of the uncertainty in the disruption of the WDN

To further examine the effect of the uncertainty in the disruption of WDN on the dynamics of the stakeholders, a Monte Carlo simulation was performed in AnyLogic where the values of the two input parameters that describe the intensity and the length of the WDN disruption are varied. The value of the households' *probability of being affected* is randomly drawn from a uniform distribution with a minimum value of zero and a maximum value of one. The average duration of households' *network-supply disruption* is randomly drawn from a uniform distribution between one day and 21 days (as the maximum value observed in the WDN resilience simulation for the scenarios of disruptions analyzed). Figure 4.8 shows the resulting distributions of the number of different types of tanker orders in addition to the average waiting time for completed orders and the average duration of households' water runout. The vertical axis in the sub-figures in Figure 4.8 represents the probability of the occurrence of the values in the horizontal axis based on 1000 runs of the simulation.

The results in Figure 4.8 show that the number of completed free orders and the number of completed high-price orders are more sensitive to the variation in the disruption of WDN. On the other hand, the number of completed regular orders is less sensitive to the variation in the attributes of the disruption of the WDN, suggesting that the effect of the interplay between the household and the tanker agents is reflected in the demand for free and high-price tankers. Another reason for the relatively lower variability in the results for completed regular tanker orders is that this type of order is given the least priority by tankers as a result of both the profit-seeking behavior of both classes of tankers and the utility-policy of giving priority to free tanker orders. As a result, most of the regular tanker orders end up among the uncompleted orders.

The results in Figure 4.8 also show that as the average household's runout duration increases, its probability of occurrence generally decreases. However, it may take the IWS system (i.e., the WDN and the tanker market) up to 190 hours (7.9 days) to provide all households with running water. Almost 15% of the time, the tanker market was able to completely eliminate the effects of the disruption of the WDN on households, resulting in no household water runout. The average waiting time for completed orders represents the collective effect of the interactions between the behavior of the stakeholders, and it directly affects the average duration of the household's runout.

However, the average waiting time for completed orders tends to be greater since some households generate requests for tankers before running out of water.

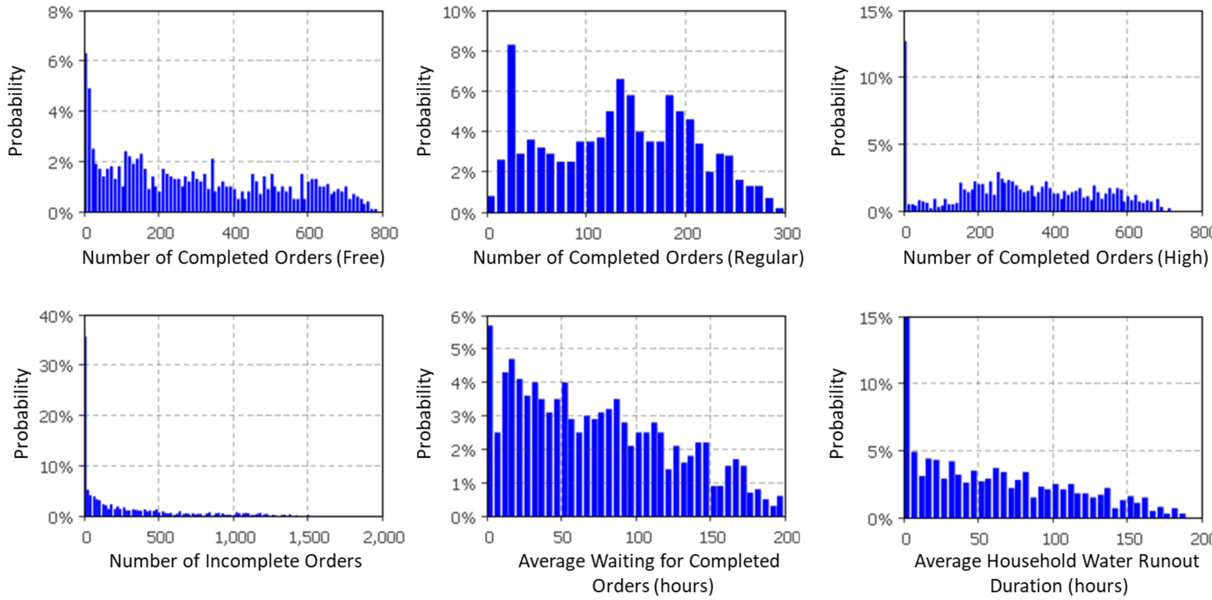


Figure 4.8. Impact of stochastically varying the attributes of the disruption of the WDN on the number of completed free, regular-price, and high-price tanker orders, number of incomplete orders, average waiting time for completed orders, and the average household water runout duration based on 1000 simulation runs

To analyze the dynamics of household agents during stochastic disruptions, Figure 4.9 shows the changes in the percentages of households in the five states where the household agents exist (see household agent state chart in Figure 4.2) over the simulation time. The darker the color in the graphs, the higher the probability of being closer to the median of all simulations. The results for the regular and the high-price tankers show more dynamic behavior as households switch between different types of tanker orders as the attributes of the tanker market change. The sudden drops in the percentages of household agents in the graphs of the regular tankers and the high-price tankers are due to the introduction of free tankers as an option to households when running out of water. The IWS system is most likely to completely recover (i.e., all households are satisfied either by tankers or by returning network-supply) anytime between 5.4 days and 9.1 days, but may take up to 18.7 days.

The variation in the results in Figure 4.9 indicates that the IWS system is sensitive to the intensity of the disruption of the WDN and the duration of the impact on households' network-supply.

Higher intensity of the disruption increases the number of affected consumers and the demand for water tankers, while a longer duration of the disruption of WDN-supply to households increases the dependency of households on the tanker market as the only way for recovery.

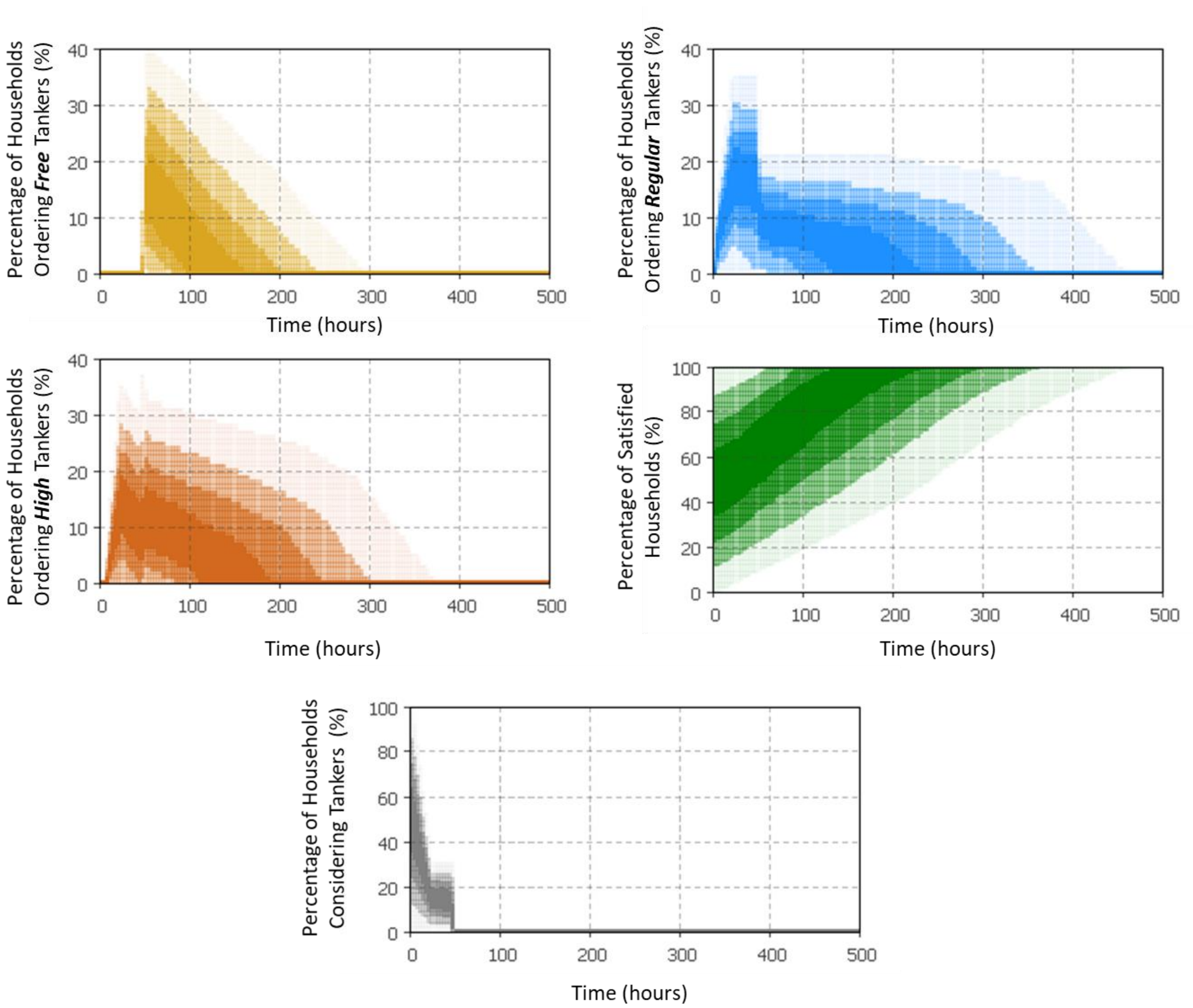


Figure 4.9. Impact of stochastically varying the attributes of the disruption of the WDN on the number of percentage of households in each state of the household agent based on 1000 simulation runs

4.3.2 Parameter Variation

The purpose of the parameter variation analysis is to assess the impact of the input parameters on the ABM using the parameter variation features in AnyLogic. To study the impact of a specific parameter, the parameter is deterministically varied within a user-defined range and at user-defined increments while fixing other parameters at the base value. Table 4.3 specifies the ranges of the parameters included in the parameter variation along with the rationale for their variation. Many cities in the Middle East have an IWS system configuration similar to the one of the case study city (e.g., Klassert et al. 2015). Therefore, analyzing the impact of the variation of the parameters related to household preferences and to the tanker market can reveal different behaviors that may emerge in other cities.

Since the uncertainty in the disruption of the WDN affects the outcomes of the ABM, the parameter variation is performed for two disruption scenarios to assess whether the change in the disruption attributes would affect the impact of varying the parameters. A low-intensity disruption (25% of households are affected) and a high-intensity disruption (100% of households are affected) are considered representing the disruption of one DMZ of the WDN and the disruption of all four DMZs, respectively. For both disruption scenarios, the median value of the average duration of household network-disruption is assumed (=250 hours). Parameter variation is carried out for each disruption scenario separately.

Table 4.3. Parameters evaluated in the parameter variation analysis

Parameter group	Parameter	Base value (unit)	Range (increment)	Rationale
Household Preferences	Households' probability of vending water *early* by tanker truck (i.e., consumer's risk aversion attitude)	0.71	0.1-1 (0.1)	Household preferences may change over time as households adapt (in the long term) to the WDN disruption. The household survey indicates that household behavior changes if they have previous experience(s) with disruptions. Household preferences also change from one city to another.
	Probability of the willingness of the household manager to pay more for faster delivery (arrives the same day)	0.64	0.1-1 (0.1)	
	Probability of the willingness of household manager to wait in line (for more than 1 hour) to obtain a free tanker	0.44	0.1-1 (0.1)	
Tanker Market/Utility Policy	Number of utility-regulated tankers	15	5-25 (5)	The number of tankers in the city changes over time. As the utility improves the network supply (which is the current utility plan), the demand for tankers during normal operation conditions decreases, and fewer tankers will be available during disruptions. The number of tankers available during partial disruptions of the WDN may be greater since tankers from all over the city can supply to the affected households.
	Capacity of filling station	4 (tankers/hour)	2-10 (1) tankers/hour	Proportional capacity of filling stations for the analyzed sub-network

4.3.2.1 Household Preferences Parameters

Household preferences include three parameters, the probability of ordering a water tanker early (before running out of water), the probability of paying higher prices for faster tanker delivery, and the probability of the willingness to wait in line for a free tanker at the filling station. The results of the household survey suggest that household preferences change over time and that households' prior experience with the tanker market affects their preferences. The results of the parameter variation of the household preferences parameters are shown in Figure 4.10, Figure 4.11, and Figure 4.12, showing the impact of the parameter variation on the average household's runout duration and on the proportion of completed orders of each tanker type for both the low-intensity and the high-intensity disruption scenarios.

The probability of ordering early has an impact on the distribution of the different types of tanker orders both before and after the time when households run out of water. Increased number of households ordering early helps flatten the demand curve for tankers and decreases the demand-supply gap when households run out of water. Figure 4.10 summarizes the results of the impact of varying the probability of ordering early on the outputs of the ABM. For both disruption scenarios, the average runout duration decreases (to a certain point) as the probability of ordering early increases. A 10% increase in the probability of ordering early may result in a reduction in the average runout duration of up to 15 hours. However, increasing the probability of early ordering can minimize the runout duration up to a certain point where the volume of early orders exceeds the capacity of the tanker market. This breaking point is explained by the change in the trend of the number of regular-price and high-price tanker orders.

The behavior of households switching from higher-price to regular-price tankers indicates decreasing waiting times for orders (and decreasing runout durations) and visa-versa. The impact of varying the households' probability of paying more is greater for the low-intensity disruption scenario where the early demand of the tanker market is not as overwhelming as in the high-intensity disruption scenario. Similar to the average runout duration, the number of free tanker orders is indirectly affected by the change in the probability of early ordering since free tankers are not an option for households before running out of water.

The difference between the variance for the low-intensity and for the high-intensity scenarios is found to be statistically significant for both the number of completed free, regular, high-price orders (using the F-Test of variance at 5% confidence interval). This suggests that the intensity of the disruption affects the impact of the change in the households' probability of ordering early on the distributions of different types of tanker orders. The lower the intensity of the disruption, the greater the impact of the change in the households' probability of ordering early.

The results in Figure 4.10 show that, depending on the intensity of the disruption, increasing the households' willingness to order early can have an impact in reducing the average runout duration for households. The utility can maximize the reduction in runout durations by increasing the number of early orders and/or increasing the duration during which households order early. One possible utility policy to increase the number of early orders is to provide free tankers as an option for early orders. On the other hand, increasing the duration for early orders can be achieved by having an effective communication with affected households to inform them about the scale of the disruption and the expected time for supply recovery. Based on the results of the household survey, households tend to consider water tankers only one or two days before their water storage runs out since they usually have no information about the time of supply recovery. Some households may be willing to order earlier than two days before running out of water to avoid longer waiting times and possible water runout if they are provided with sufficient information about the disruption by the utility.

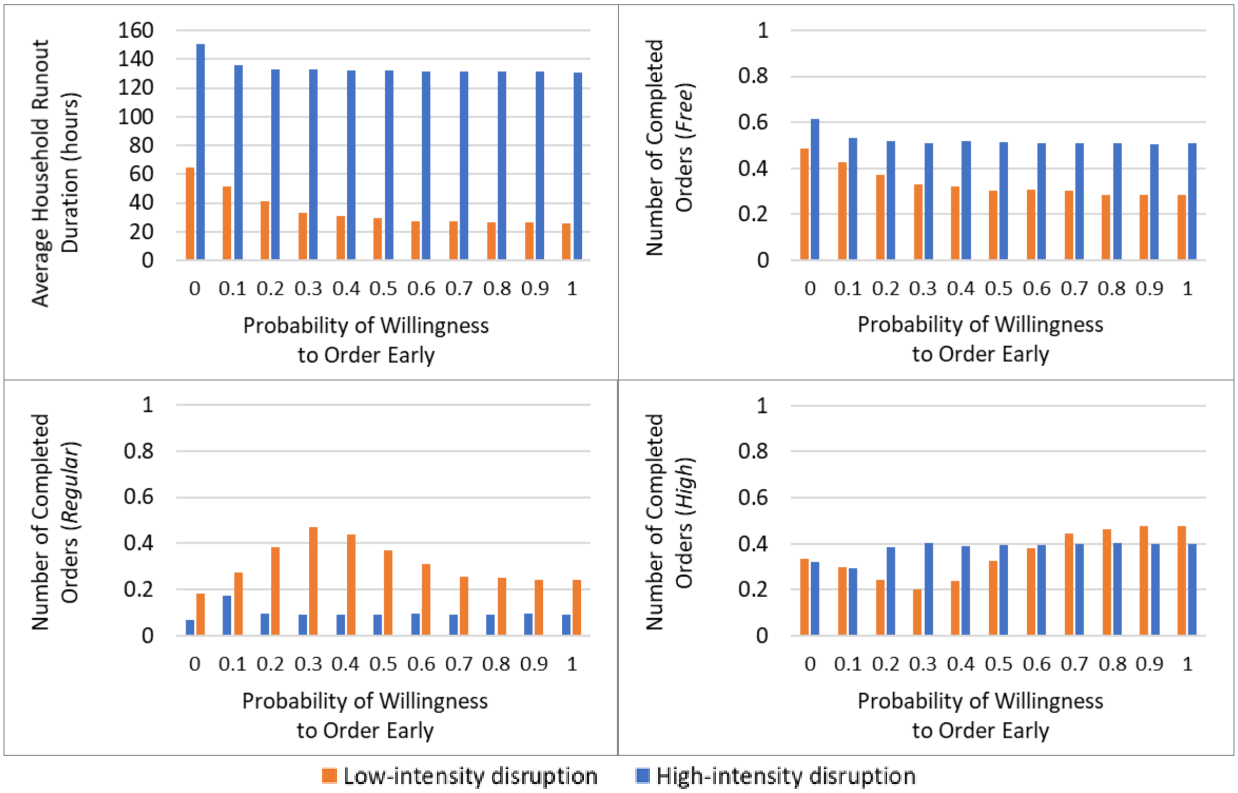


Figure 4.10. Impact of varying the probability of household's *willingness to order early* on the network-average household runout duration, the number of completed high-price orders and the number of completed regular orders for (a) low-intensity disruption and (b) high-intensity disruption

Increasing the probability of households' willingness to pay higher for faster delivery of water tankers shows a reduction in the average runout duration (Figure 4.11). Greater household demand for high-price tankers draws the utility-independent tankers to the household tanker market, which increases its supply capacity. However, the limited number of utility-independent tankers can provide improvement to the system's performance to a certain point, after which the percentage of high-price orders increases but with no reduction in the average runout duration.

Although the increase in the percentage of high-price orders may help in reducing the overall average runout duration, it may introduce an inequality among high-income and low-income households in terms of the waiting times for tanker orders. Households who are willing to pay higher for water tankers (driven by their financial well-being, as found in Chapter 3) get the water tankers at shorter waiting times while causing longer waiting times for households ordering regular-price tankers.

Both the low-intensity and high-intensity scenarios show a similar level of sensitivity to the change in the households' willingness to pay more for tankers, except for the number of free tanker orders. The variance in the number of completed free orders for the two scenarios was found to be statistically significantly different (using F-test of variance at 5% confidence interval). The greater the intensity of the disruption, the greater the impact of the change in the households' probability of paying more on the number of completed free orders.

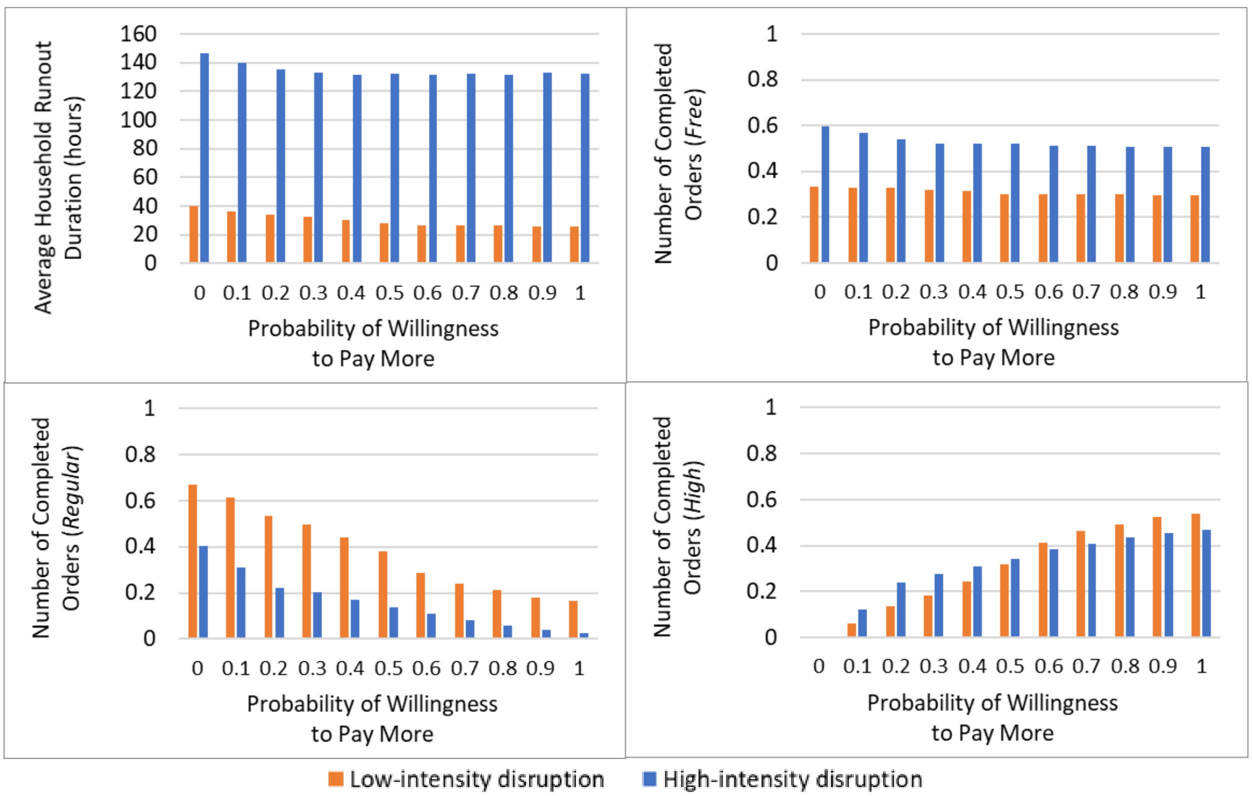


Figure 4.11. Impact of varying the probability of household's *willingness to pay more* for faster delivery of tankers on the network-average household runout duration, the number of completed high-price orders and the number of completed regular orders for (a) low-intensity disruption and (b) high-intensity disruption

The results in Figure 4.12 show that increasing the probability of the household managers' willingness to wait in-line at the filling station negatively impacts the performance of the tanker market by the slight increase in the average runout duration. The increasing demand for free tankers decreases the percentage of households ordering high-price tankers, which minimizes the effect of utility-independent tankers in improving the supply capacity of the tanker market.

Increasing the households' willingness to wait in-line for free tankers could not completely eliminate the demand for other tanker types since free tankers are not available for early tanker orders. The results show a lower share of completed regular-price tanker orders as the willingness to wait in-line increases, reflecting the behavior of more households switching to free tankers while waiting for regular-price tankers. The same trend is observed for the percentage of the completed high-price tankers for the high-intensity disruption scenario (blue bars). However, the impact of greater demand for free tankers on completed high-price orders is less significant in the low-intensity disruption scenario (orange bars) since most of these orders were completed before households run out of water. Using the F-test of variance, the difference between the variances in the number of completed high-price orders for the low-intensity and high-intensity disruptions is found to be statistically significant at a 5% confidence interval.

The results of varying the probability of the willingness to wait in-line further stresses the trade-off between the households' runout durations and the equality in waiting times. Obtaining free tankers at the filling station ensures equality among high- and low-income households based on a first-come-first-served basis, but it may result in a longer overall average runout duration. The utility can explore these tradeoffs to test different policies for the tanker market.

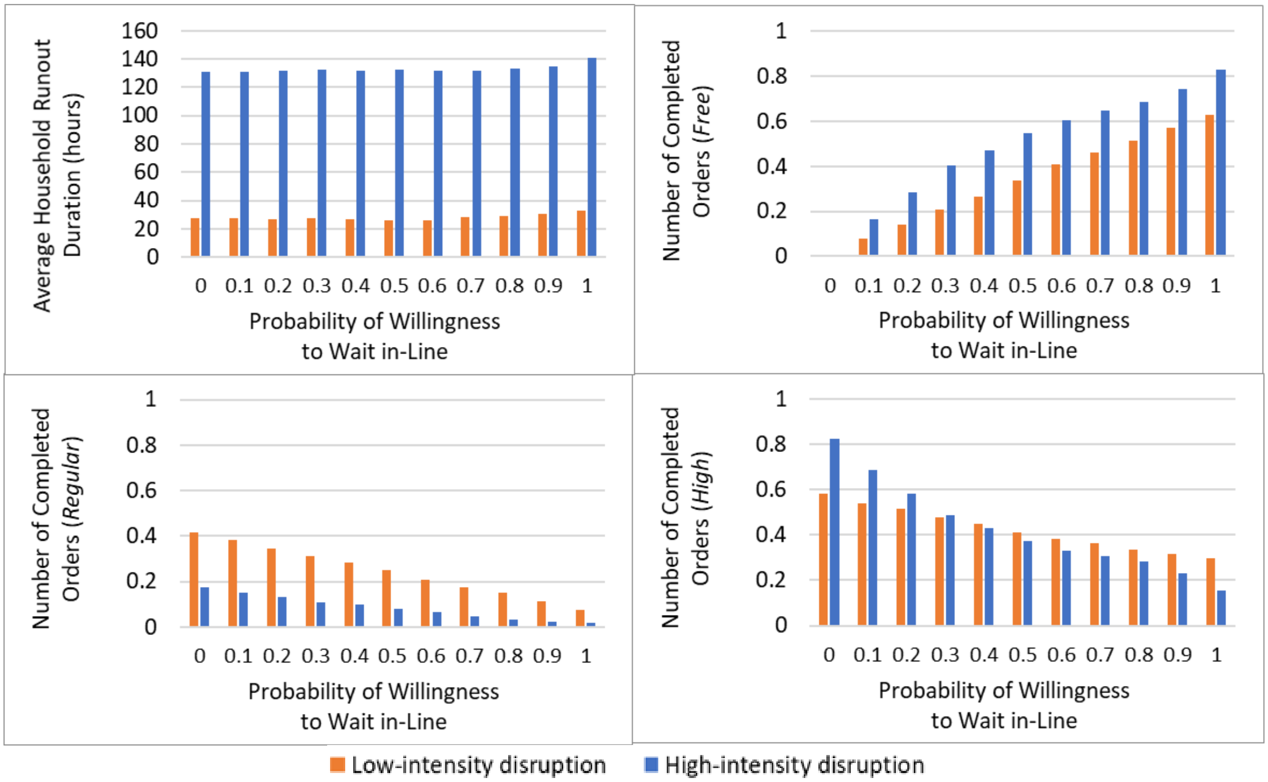


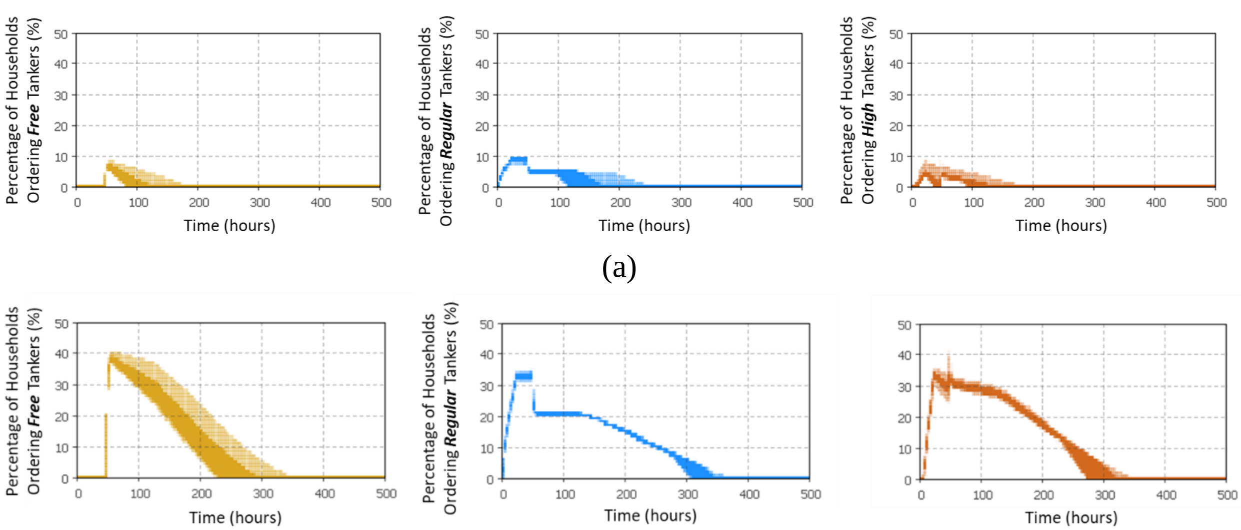
Figure 4.12. Impact of varying the probability of the household's *willingness to wait in-line* for free tanker on the network-average household runout duration, the number of completed high-price orders and the number of completed regular orders for (a) low-intensity disruption and (b) high-intensity disruption

4.3.2.2 Tanker Market Parameters

The two parameters of the ABM that determine the capacity of the tanker market are the number of the available tanker trucks and the capacity of the tanker filling station(s). The base value for the number of available tankers represents a proportional number appropriate to the analyzed number of household agents based on the total number of available tankers in the city. However, during partial disruptions of the WDN, tankers from all over the city can provide supply to the affected households within the impacted areas of the network, resulting in a greater number of available tankers. On the other hand, the utility's long-term improvement of the supply of the WDN could reduce the demand for tankers during normal operation conditions, which results in fewer available tankers during disruptions. The outputs of the ABM are analyzed to assess the impact of scenarios of the increased and decreased number of available tankers.

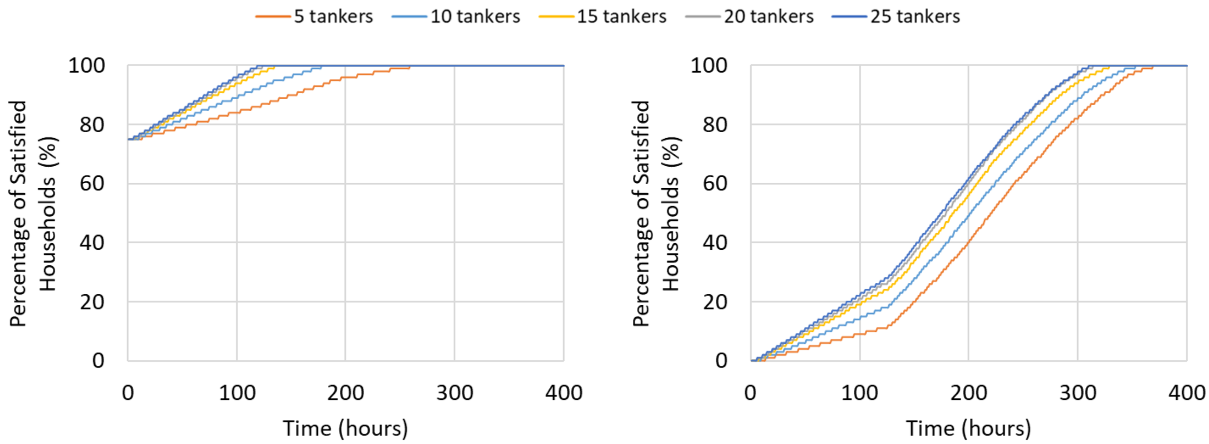
The parameter of the capacity of filling station(s) can represent the system's ability to fill tankers from water sources available to tankers both provided by the utility or from private wells. When tanker demand is high and prices are increased, tanker agents may obtain from water sources other than the filling station(s) that is provided by the utility due to the longer waiting times for filling.

Figure 4.13 shows the impact of varying the number of available utility-controlled tankers on the percentage of households for different types of tanker orders over time. The effect of the increased number of tankers is two-fold. A greater number of tankers shortens the waiting times for all order types. Subsequently, the behavior of households ordering high-price tankers may change as they switch to regular-price orders if waiting times are shorter than 24 hours. The main evaluated outcome of the ABM is the percentage of satisfied households over time (Figure 4.14). The results show that the curves of the number of satisfied households over time are linear for low-intensity disruptions but tend to follow a Gaussian distribution for high-intensity disruptions. In both cases, these distributions are scalable with the change in the number of available tankers. The results show that increasing the number of tankers can improve the speed of recovery for affected households until the system becomes limited by the capacity of the filling station(s) (when the number of tankers is 20 or greater).



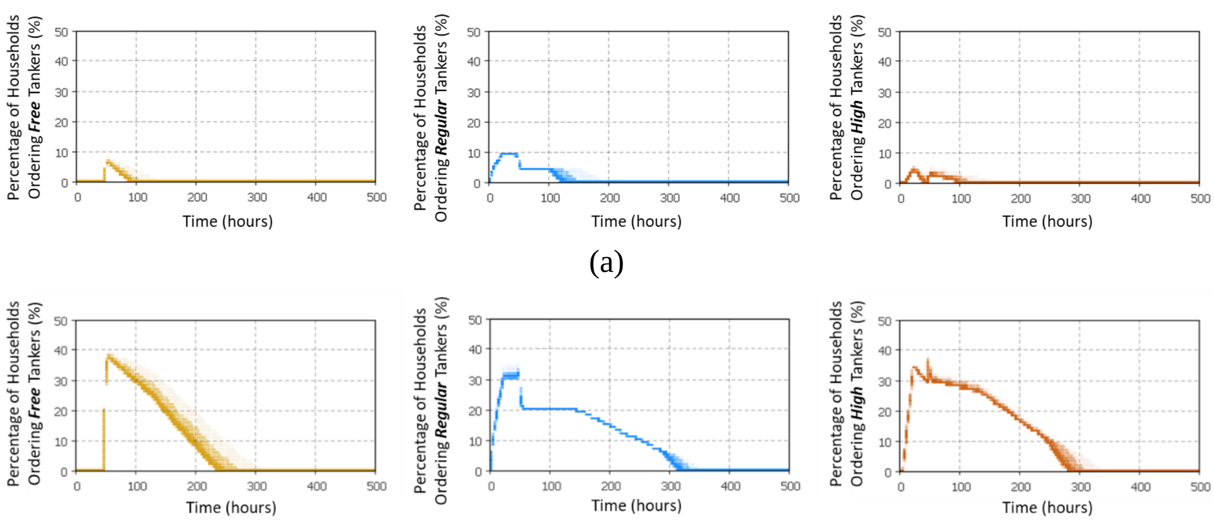
(b)

Figure 4.13. Impact of varying the number of tankers on the percentage of households waiting for different types of tankers over time for (a) low-intensity disruption and (b) high-intensity disruption



(a) (b)

Figure 4.14. Impact of varying the number of utility-controlled tankers on the percentage of satisfied households for (a) low-intensity disruption and (b) high-intensity disruption



(a)

(b)

Figure 4.15. Impact of varying the capacity of the filling station on the percentage of households waiting for different types of tankers over time for (a) low-intensity disruption and (b) high-intensity disruption

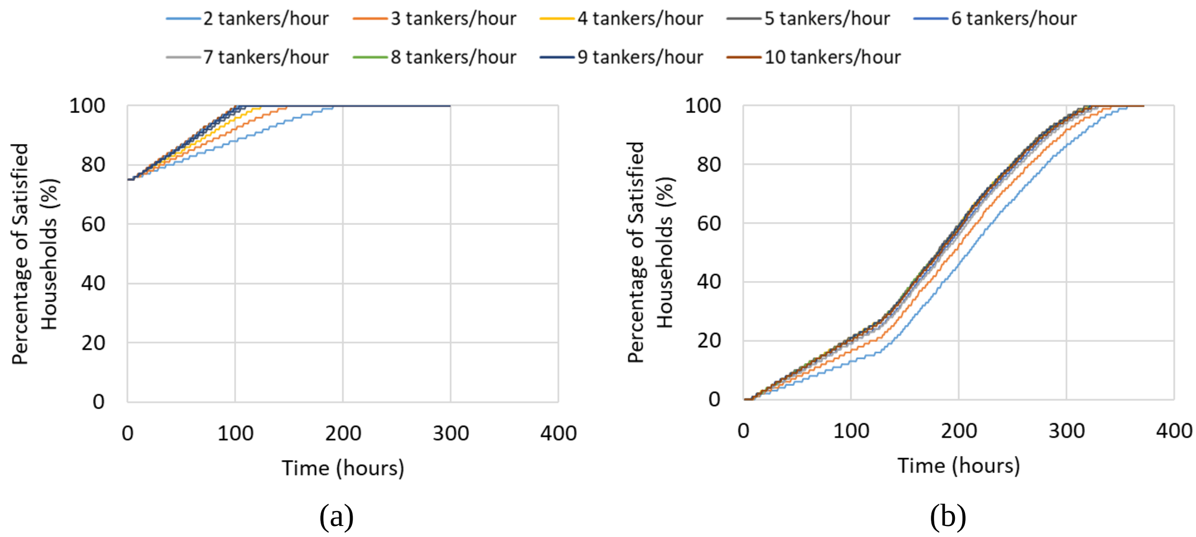
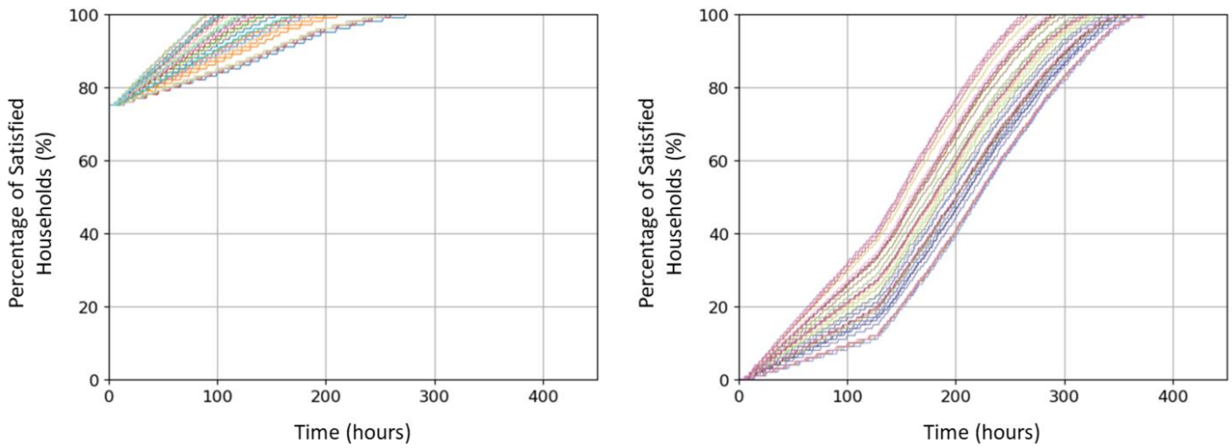


Figure 4.16. Impact of varying the capacity of the filling station on the percentage of satisfied households for (a) low-intensity disruption and (b) high-intensity disruption

Varying the capacity of filling tankers shows a small variation on the percentage of different types of tanker orders (Figure 4.15). Increasing the capacity of filling tankers (while fixing the number tankers at the base value) can improve the recovery of affected households until the system becomes limited by the number of available tankers (when the filling capacity is five tankers/hour or greater) (Figure 4.16). The results suggest that the system under base values is operating close to its full capacity in terms of the number of tankers given the diminishing impact of varying the filling capacity. The curves in Figure 4.16 are also scalable, similar to the trends resulting from varying the number of available tankers.

The results show that the number of tankers and the capacity of filling are both limiting factors for the capacity of the system to fulfill households' demand in a timely manner. The effectiveness of increasing the resources for one factor is dependent on the available room of improvement determined by the other factor. Theoretically, when both the number of available tankers and the capacity of the filling station are systematically varied (within the defined ranges and increments in Table 4.3), the results show further possible improvement in the recovery of affected households (Figure 4.17). The policy interventions to improve these two parameters are different and involve different costs and implementation considerations. Increasing the number of tankers may be achieved by lifting the thresholds on the selling price to draw more investors to the tanker market while increasing the capacity of filling stations would require long-term investment in installing new filling stations or improving existing ones. Therefore, the utility should explore a mixture of policy interventions that optimize these aspects of performance and cost.



(a) (b)

Figure 4.17. Impact of varying the number of tankers *and* the filling station's capacity on the percentage of satisfied households for (a) low-intensity disruption and (b) high-intensity disruption (results for all 42 possible combinations)

4.4 Verification and Validation

The verification and validation were carried out throughout the model development using four steps: (1) validating the conceptual model, (2) verification of the computerized model, (3) data validity, and (4) external validation (Sargent 2010). Validating the conceptual model ensures that the logic, structure and assumptions of the conceptual model represent the real IWS system. To validate the conceptual model, face-to-face meetings were conducted in December 2018 and in January 2019 with Subject Matter Experts (SMEs) who have knowledge and experience with the water supply system in the case study city. Six SMEs, including university professors, utility engineers and managers, and water consultants with at least 8-year of experience with the system, were involved in the verification and validation. The SMEs verified the model assumptions, logic, and relationships, including the objectives and the decision rules for the household and the tanker agents. The SMEs validated the model representation of the system as reasonable for the intended purpose of the ABM. The consideration of utility-independent tankers in the ABM was based on the suggestions of two of the SMEs since they often supply to households during network disruptions. The SMEs also validated the model assumptions that were obtained from the household survey as reasonable and representative.

Computerized model verification refers to ensuring that the computer programming and implementation of the conceptual model is correct (Sargent 2010). The verification of the computerized model was done by first building a simple version of the model and verifying its results by running different scenarios. More components were gradually added to the model while validating and testing the intermediate results for each model step. The visualization tools provided in AnyLogic allowed tracing of the status of the household and the tanker agents to verify their behavior and their transitions between states. The detailed results of each of the combinations of the two disruption scenarios were carefully examined and the explanation of any unexpected behavior was tested and verified. In addition, the analysis included stochastic simulation and parameter variation (i.e., sensitivity analysis), and the model responses to these experiments (including the behavior of households and the measures of the performance of the tanker market such as the average waiting time for completed tanker orders and the average household's runout duration) were consistent and logical. Multiple runs of the stochastic simulation were performed to ensure that the level of stochastic variability in the model is minimal, reflecting the consistency of the model (Sargent 2010). The testing of extreme values of the model parameters was also done to ensure a consistent model response.

Data validity ensures that the data used for model development, testing and experimenting are correct and accurate (Sargent 2010). Data used in the ABM are based on the household survey, in-person and phone interviews with utility personnel, the utility website, and some news articles. Household preferences were identified and estimated based on the results of the household survey. The validation of the household survey was presented earlier in Chapter 3. As discussed in Section 3.5, the different types of tanker orders were determined based on personal interviews with utility personnel in July 2017. The responses of households in the survey confirmed the types of tanker orders as the available options for households. The structure of the household agent, including the agent states and transitions, were based on the results of the survey as well. The number of tankers and capacity of the filling stations were estimated based on phone interviews with utility personnel. The policies of the water utility were determined based on the utility website, news articles, and phone interviews with utility personnel.

The external validation of the model findings was done by confirming the results with relevant studies in the literature (Table 4.4).

Table 4.4. External Validation

Relevant Finding/Discussion	Study(s)
The utility-independent tankers (sometimes illegal) have a positive contribution in performance of the IWS system	Srinivasan et al. (2010c); Klassert et al. (2015); Cain (2018); Zozmann et al. (2019)
Inequality in the supply of water tankers between low-income and high-income households	Raina et al. (2018)
During disruptions of the water supply infrastructures, the capacity of filling stations may become a limiting factor for the tankers market	Gupta and Quick (2006)
Higher demand for tankers promotes unregulated (or illegal) tanker operations	Gupta and Quick (2006); Mustafa and Talozi (2018); Zozmann et al. (2019)

4.5 Summary and Conclusions

This chapter introduced an Agent-Based model to analyze the dynamics and the interactions of the stakeholders in the IWS system when responding to disruptions in the WDN. The ABM models the decision making of household managers to choose between non-piped water sources with different prices and waiting times. Household managers aim to minimize the time of running out of water given their preferences related to their attitude towards the risk of running out of water (which affects the timing of their decision), their willingness to pay, and their willingness to wait in-line. The model assesses the dynamic interactions between households' decisions and the response of agents in the water tanker market and vice versa. The model also assesses the impact of the utility's policies both related to affected households and related to the tanker market on the overall performance of the IWS system represented by the duration of households' water runout. The proposed modeling approach integrates the resilience analysis of the WDN into the ABM using two input parameters: the number of affected households and the average duration of the household's network-supply disruption.

The ABM was implemented in the context of the IWS system in a city in the Middle East using a representative subset of the whole network. Household preferences were obtained from empirical data based on a household survey of 442 households in the city. The dynamics of households and the impact of their interactions with the tanker market (given the policies of the water utility) were analyzed under deterministic and stochastic scenarios of the disruption of the WDN. In addition, a parameter variation analysis was carried out to assess the impact of the input parameters on the outputs of the ABM to assess the possible variation of input parameters across time and location (i.e., different cities with similar system configuration).

One of the main findings related to the first hypothesis in this chapter is the impact of the intensity and the length of the disruption of the WDN on the dynamics of households and the performance of the IWS system. The results of both the deterministic and the stochastic scenarios of the disruptions of the WDN show that, with greater intensity and/or duration of the WDN disruption, households tend to divert from regular-price tankers and concentrate their order patterns more on the free or high-price tanker categories. In addition, the intensity and the length of the disruption of the WDN are positively correlated the numbers of *completed* free and high-price tanker orders while negatively correlated with the number of regular-price tanker orders, showing that it is less likely for regular-price orders to be completed in scenarios that exhibit greater disruption intensity and/or duration.

Another finding that has implications on future research is that short-term households' behavior in the multi-mode IWS system in response to disruptions is mainly logical and follows simple scalable patterns, despite the interdependencies of households' decision making and households' heterogeneity in terms of preferences related to obtaining non-piped water. Households' behavior, in the form of the distribution of different types of tanker orders, scale linearly with the intensity and the duration of the disruption of the WDN. This finding suggests that the second hypothesis in this chapter, which states that stakeholders' interactions can lead to an emergent behavior, should be rejected under the current assumptions of the ABM model. This resulting logical behavior may be due to the interactions between household agents being indirect (occurs through the changes in the model environment of the ABM model). Therefore, part of the future work of this research is to modify the ABM model to consider other configurations of IWS systems where households have *direct* interactions (tanker sharing, sharing of stored water, etc.) in which emergent behavior may exist. In addition, analyzing stakeholder interactions on the long-term over multiple disruptions, where stakeholders learn from and adapt to repeated disruptions, may result in an emergent behavior.

Another important finding is related to the trade-off between supply inequality and the overall system performance. The results of the parameter variation analysis revealed that greater demand for high-price tankers reduces the overall average household runout duration, but it causes longer waiting times for households with regular-price orders. Moreover, the majority of incomplete orders are comprised of regular-price tanker orders since they are given the least priority in the tanker market. One of the reasons for the utility's price policy is to ensure the supply of tankers to all households at affordable prices. The results of the variation of the willingness to wait in-line also show that when all households were forced to wait in-line for free tankers as the only option (which ensures equality among low-income and high-income households), the system's average runout duration increased due to the absence of the incentive for the utility-independent tankers to enter the household tanker market. The utility should balance these trade-offs when planning for policies related to the tankers supply in the city.

One of the findings from the parameter variation analysis is that the improvement of one parameter can lead to a limited impact on the overall system performance since the system becomes limited by the value of other parameters. The performance of the system (in terms of the average household's runout duration) is a result of the interdependencies among the parameters of the households' preferences and the parameters of the tanker market. For instance, the impact of increasing the households' willingness to pay more for faster delivery is dependent on the capacity of utility-independent tankers. Similarly, the impact of increasing the number of utility-regulated tankers is dependent on the capacity of filling stations.

4.5.1 Significance of the Study

Previous research on IWS systems has focused on analyzing the long-term dynamics of different components of the system (namely, the WDN, households, the market of non-piped water, and the utility) in isolation, assuming static behavior of the other components. The short-term interactions between the four components of the IWS system in response to disruptions were not addressed in prior studies. The main contribution of this chapter to the body of knowledge is the modeling, evaluation, and validation of the interactions between the behavior of stakeholders in IWS systems in response to disruptions. The proposed modeling approach contributes to the body of knowledge by considering the coupling of the WDN and the stakeholders of the IWS system. This coupling addresses the heterogeneity among households in terms of the impact on the WDN and enables the evaluation of the impact of the dynamics in the disrupted WDN on the behavior and interactions of stakeholders in the IWS system. In addition, the model addresses the heterogeneity in households' preferences related to their willingness to pay and/or wait for non-piped water sources. The analyses presented in this chapter highlighted how the variation of households' preferences affects the overall performance and the supply equality of the non-piped water market.

The developed ABM provides insights regarding the operation of the non-piped water market. Water utilities can use the ABM to assess the impact of different policies related to managing, coordinating, and/or controlling the operation of non-pied water sources during disruptions of the WDN. The results in this chapter showed possible improvements to the performance of the tanker market that can be achieved by implementing policies to encourage households to act early to disruptions, increase the number of available tankers, and/or increase the capacity of filling stations. The model can also assist utilities in evaluating the impact of different policies on utility-independent tankers and their contribution to the overall system performance. In addition, the utility can use the model and its results to balance the trade-off between system performance and supply inequality and assess the impact of different policies on these two outputs. The utility can also vary the input parameters to identify the systems' limiting factors (such as the number of tankers and the capacity of filling stations) that can be targeted to improve the system's performance. The coupling of the WDN and the non-piped market enables water utilities to assess the impact of recovery strategies for the disrupted WDN on the non-piped market.

4.5.2 Limitations and future work

The work presented in this chapter has some limitations. First, the implemented model is, in part, specific to the IWS in the case study city. However, the main findings from the case study are generalizable for IWS systems with similar configurations in terms of the types of non-piped sources and their interdependencies. The analysis of the parameter variation described possible behaviors that may emerge in similar IWS systems. In addition, the proposed model considers three general categories of non-piped sources: a faster high-priced source, a slower low-priced source, and a free source involving traveling and/or waiting in-line. Thus, the proposed model can be applied to any IWS system that has similar categories of non-piped sources by changing their waiting times and changing the values of the input parameters related to households' preferences and the tanker market. The model can also be modified to incorporate any utility policy specific to the IWS under study.

Another limitation related to the modeling approach is that the ABM assumes a one-way effect of the dynamics of the disruption on the behavior of stakeholders. The impact of the supply provided by the tankers on the hydraulics of the WDN during the disruption is not addressed. In future work, feedback from the ABM to the WDN can be used to update the water levels in households' storage tanks (after obtaining supply from water tankers), and thereby explore the impact on the hydraulic performance of the WDN during the disruption by reducing the demand for the piped-water.

The ABM assumes a static behavior of the water utility in the form of utility policies regarding the affected households and the tanker market. However, the behavior of the utility can be dynamic during system disruptions (e.g., in the form of communicating with households and/or providing supply from emergency storage tanks). Future research could include incorporating the dynamic behavior of the utility and testing other possible utility policies, including communicating with affected consumers to provide information about the scale and the duration of the disruption, controlling households' tanker supply by tanker sharing, and lifting price-controlling policies for tankers.

A known limitation of Agent Based Modeling, as a micro-modeling approach, is the requirement of higher computational power. However, the ABM developed in this research took between 5 and 15 seconds to complete one run of a deterministic scenario (using Intel Core i7-8665U with 32 GB RAM). The variation in computational time depends on the intensity and the duration of the disruption (i.e., number of affected households and the average duration of being affected). This relatively low computational time allows the future applications of this ABM model at a greater scale (for instance, at the city scale) with a greater number of household and tanker agents. It also allows the inclusion of other classes of water consumers (such as commercial and industrial water consumers) and/or additional agent interactions.

Future research is also recommended to include the analysis of the cost burden of the disruptions of the IWS. The presented analysis in this chapter does not address the distribution of the financial burden of the disruption among households and between households and the utility. Although some scenarios of input parameters may improve the system's performance, they may shift the financial pressure from the utility to households or vice versa. The household cost burden is determined by aggregating the expenses incurred by households throughout the duration of being out of water in addition to the cost of the tanker if obtained. These costs can be estimated by considering the increase in the demand for bottled water for households waiting for tanker supply. In addition, a detailed demand-supply pricing relationship for water tankers should be established to estimate the cost of tankers for households. On the other hand, the utility's cost burden could include the cost of free tankers provided to affected households.

5. CONCLUSIONS AND RECOMMENDATIONS

The analysis of the resilience of intermittent water supply (IWS) systems requires special considerations related to the hydraulics of the water distribution network (WDN) and the dynamics of the stakeholders of the IWS system. The intermittent WDN is characterized by household water storage, significant pressure fluctuation, and pressure-dependent household demand, which results in supply inequity among households, especially during disruptions of the WDN. Stakeholders of the IWS system (including households, the utility, and non-piped water providers) respond to the disruptions of the WDN in a dynamic way due to the existence of the non-piped water market. This dissertation aimed to bridge the gap in the body of knowledge and practice regarding the assessment of the resilience of IWS systems and the impact of the dynamics and the interactions among the system's stakeholders on the resilience of the system. The first section of this chapter provides an overview and summary of the research. The second section summarizes the results of this dissertation for each research objective. A discussion of the significance of the research to the body of knowledge and practice is presented in the third section of this chapter, followed by a discussion of the underlining limitations of the research. Finally, the chapter concludes by proposing recommendations for future research.

5.1 Summary of the Research

The overall objective of this dissertation is to evaluate the resilience of IWS systems by modeling and evaluating the dynamics of the system's component (focusing on the WDN and the household consumers) and the interactions within components under disruptions of the WDN. The research activities in this dissertation were demonstrated in the context of the IWS system in a case study city in the Middle East, where households rely on in-house water storage to adapt to the supply intermittency. A survey of 442 households in the city was used to understand households' characteristics and preferences and to model the household's decision during events of disruption of the piped WDN. The dynamics and the interactions between the stakeholders of the IWS in response to disruptions are modeled and evaluated using agent-based modeling. Subject matter experts, with background and experience with the IWS system in the case study city, were involved in the development and validation of models developed in this research.

The first component of this dissertation presented a new framework for assessing the resilience of the WDN in IWS systems against acute physical disruption. The framework incorporates the aspects of IWS by modeling the filling and emptying processes of household storage tanks and by modeling supply cycles to network zones based on pre-defined schedules. The framework uses hydraulic modeling and network analysis tools to track two performance measures (Serviceability Index and Network-Average Tank filling Ratio) to assess the overall system resilience in addition to capacity-specific resilience for the absorptive, adaptive, and restorative resilience capacities. The framework was implemented and evaluated using a representative subset of the WDN in the case study city. Two disruption scenarios (pipe-damage and source-disruption) were analyzed to evaluate the network response to internal (partial) and external (network-wide) disruptions. A set of combinations of household tank capacity, the timing of the occurrence of the disruption (with regard to the supply schedule), and the length of the damage for both disruption scenarios were simulated. The sensitivity of the network performance outputs (including overall-system resilience, the number of affected households, and the duration of being affected) to the input parameters was evaluated and discussed. In addition, the framework was used to evaluate the adaptive response of the utility in terms of modifying the supply schedule during the disruption, and its impact on the network resilience was assessed.

The second component of this dissertation addressed the decision-making behavior of households in response to disruptions in the WDN. The main objective of this research component is to identify and evaluate the factors that affect the decision-making for household managers regarding obtaining water from non-piped sources. A household survey was developed, evaluated, and deployed to households in the case study city to obtain information about their water supply and consumption behavior during normal operation and during disruptions of the WDN. Based on the results of the survey, a set of binary probit models were developed to model the decision of the household manager regarding the timing of their response to the disruption (which represents their attitude toward the risk of running out of water), their willingness to pay more for faster delivery of water tankers, and their willingness to pay to avoid waiting in-line at the tanker station/location. The estimation results of the binary probit models where evaluated and the impacts of the independent variables, including household characteristics, wealth, age and occupation of household's manager, their knowledge about their households' water situation, and their prior experience with disruptions were discussed.

The third component of this dissertation analyzed the dynamics and the interactions between the components of the IWS system, including the WDN and the stakeholders, when responding to disruptions to piped water supply. An Agent-Based Model (ABM) was developed to model the decision making of household managers and non-piped water vendors and their interactions with each other at the model-environment level given the policy set by the water utility to manage the market of non-piped water. Household managers make decisions to choose between different types of non-piped water sources at different prices and waiting times. The model was implemented in the context of the IWS system in the case study city. Households in the case study city have the choice of three main types of non-piped water sources; water tankers at a utility-regulated price, tankers at higher prices, and free tankers provided by the utility at the tanker filling stations which involves waiting in-line. The results of the household survey were used to estimate the distribution of households' preferences parameters regarding the household's likelihood of obtaining a tanker before running out of water, the household's willingness to pay for faster delivery of tankers, and the willingness of the household's manager to wait in person at the tanker filling station. The ABM model was integrated with the resilience analysis of the WDN by considering the household's probability and duration of being affected by the piped-network disruption. The impact of the uncertainty in the disruption of the WDN on the dynamics of households and on the model's outputs was evaluated by performing a stochastic simulation of the WDN disruption parameters. In addition, the sensitivity of the model's outputs to the variation of the input parameters (related to the households' preferences and to the tanker market) was evaluated to address the possible variation of input parameters over time and across different locations of IWS systems.

5.2 Summary of the Results

The research conducted in this dissertation addresses the research questions and achieves the research objectives outlined in Chapter 1. Table 5.1 summarizes the research objectives, analysis performed and the main findings from the analysis.

Table 5.1. Research objectives, analyses performed and summary of the findings

Research objectives	Analyses performed	Summary of the findings
Evaluating the resilience of IWS infrastructures	• Resilience assessment framework • Disruption scenarios analysis	• Supply inequity among households in a supply zone depends on household storage capacity, the zone's network layout, and the zone's location and connectivity to the water sources of the whole network • Greater household storage capacity results in greater supply inequity as a result of longer tanks' filling times • Household storage capacity, recovery speed, supply scheduling, and the timing of the occurrence of the disruption (with respect to the supply schedule) determine the resilience of the network • Different combinations of direct and post disruptions result from the interactions between these four variables, which in turn creates non-linear trends of the number of affected consumers and disruption duration • Due to having different levels of supply inequity, different supply zones respond differently when being affected by the disruption. Thus, the network performance is affected by the timing of the occurrence of the damage • Direct disruptions were associated with smaller household storage capacities while larger storage capacities resulted in more post disruptions due to the greater impact of the supply inequity • The combination of longer damage durations (greater than one supply cycle) and greater storage capacity resulted in longer durations of disruption, although it resulted in greater network's resilience

Table 5.1 continued

Evaluating the short-term behavior of households in response to disruptions of the WDN	Households preferences (from the household survey)	• Majority of households (>50%) in the case study city are likely to obtain a tanker early, willing to pay for faster delivery, and willing to pay to avoid waiting in-line
	Binary-probit modeling	• Wealthier households are more likely to accept the risk of running out of water as they are willing to pay higher prices for faster delivery of tankers if needed • Awareness of the house's supply situation and past experience of ordering tankers increases the likelihood of avoiding the risk of running out of water • Households' likelihood of paying higher for faster delivery is based on household characteristics (such as house ownership status, income, size, and occupation of the household manager) • Likelihood of paying to avoid waiting in-line is based on demographic characteristics (such income and age) as well as the prior experience with the system (such as frequency and reliability of intermittent supply, prior experience of waiting in-line, and considerations of long-term actions regarding water supply/consumption) • Understanding the effects of household characteristics on household decisions assists water managers in the city to develop policies specific to groups of households to encourage/discourage specific household behaviors (for instance, policies to encourage high-income households to order early)
Evaluate the dynamics of the interactions of stakeholders during disruptions in the piped network	• Analysis of the simulation of the ABM using deterministic disruption scenarios for the WDN	• The number of completed orders of high-price tankers (in general) is correlated with the average waiting for completed orders • The number of free tanker orders is positively correlated with the average household runout duration reflecting the effect of utility policy • As the disruption's intensity and duration of impact increase, households tend to move to either high-price or free tanker options over the regular-price tankers • Both the *number of affected households* and the *length of being affected* determine the effectiveness of the tanker market in minimizing the consequences of the disruption of the WDN
	• Analysis of the uncertainty in the disruption of the WDN using stochastic simulation of the ABM - Probability of being affected	• The number of completed free orders and the number of completed high-price orders are more sensitive to the variation in the disruption of WDN • The number of completed regular orders is less sensitive, and most regular orders are not completed as a result of both the profit-seeking behavior tankers and the utility-policy of giving priority to free tanker orders •

Table 5.1 continued

	- (between 0 and 1) • Average duration of households' network-supply disruption (between 1 to 21 days)	• For 15% of the times, the tanker market was able to completely eliminate the effects of the disruption of the WDN • The IWS system is most likely to completely recover (i.e., all households are satisfied either by tankers or by returning network-supply) typically between 5.4 days and 9.1 days, but may take up to 18.7 days
	• Parameter variation (sensitivity analysis) of the ABM - Low-intensity disruption (25% affected households) - High-intensity disruption (100% affected households)	• A 10% increase in the probability of ordering early may result in up to 15 hours reduction in the average runout duration, but it has no further effect when the volume of early orders exceeds the capacity of the tanker market • Greater impact of varying the households' probability of paying more for the low-intensity disruption scenario since the early demand of the tanker market is not overwhelming • Increasing the probability of households' willingness to pay higher for faster delivery decreases the average runout duration (limited by the capacity of utility-independent tankers), but it may introduce inequality of tanker supply among low- and high-income households • Increasing the probability of household managers' willingness to wait in line at the filling station ensures equality between low- and high-income households, but may increase the average runout duration

5.3 Limitations of the Research

The focus of the current research was on the short-term analysis of the resilience of IWS systems subjected to acute physical disruptions. IWS systems are also subject to long-term (chronic) disruptions that cause different dynamics of the stakeholders. Long-term analysis of IWS would consider households' learning and adaptation (e.g., investing in increasing storage capacity) due to repeated experience of acute disruptions and/or due to the effect of continuous chronic stress (e.g., degradation of the WDN, long-term changes in availability and prices of non-piped water, and the changing policies of the water manager). In addition, the utility behavior would be treated as being dynamic in the long-term as the utility learn from disruptions and adapts over time. Although households' prior experience with the WDN and the non-piped sources were considered in this research, the households' dynamics over the long-term were not addressed.

The models developed in this doctoral research and their evaluation address IWS systems that are based on household water storage with greater households' dependence on piped-water, similar to the IWS system in the case study city. In addition, the analysis of the behavior of stakeholders assumes the existence of a non-piped water market. IWS systems can have different levels of households' dependency on different water sources (both piped and non-piped). For example, households in some IWS systems rely on private wells as the main water supply, and some households may have no connection to the piped network. In addition, the results from the case study city are limited to IWS systems with similar configurations to the case study city in terms of the types and capacities of household water storage and their operation, the operation of the intermittent supply (times and durations), and the types of non-piped water sources. Nevertheless, the developed models in this research can be modified to address different types of household storage and different types of non-piped water sources. In addition, household behavior that may exist in other IWS such as water storage sharing and water reselling can be incorporated into the ABM.

The scope of this research was limited to residential water consumers. Other categories of urban water consumers, such as commercial, industrial, and/or critical facilities, were not addressed. These types of water consumers may have behaviors different from those of households due to different objectives, priorities, preferences, and/or utility policy. For example, during disruptions of the WDN, the utility may give supply priority to critical facilities (such as hospitals) and households over commercial or industrial consumers.

The resilience analysis in this dissertation was limited to the quantity of water supply. The quality of the water supplied by the piped-network and the quality of different non-piped sources were not addressed in this research. One of the common issues in IWS is the risk of water contamination due to the process of emptying and filling pipes and due to low pressure in some areas of the network. In addition, household tanks can be a source of water contamination due to the issue of water age. Therefore, having a greater capacity of household storage poses a continuous risk of water contamination due to reduced water circulation, although it increases the network's resilience during disruptions. In addition, the quality of water in the non-piped market may affect the decision of the household.

As discussed in Chapter 2, this study did not include validation of the results related to the network performance and household behavior during disruptions, using real-world data. Acquiring actual data related to disruptions and their recovery is challenging since performance data related to disruptions (both for the water network and for the non-piped resources) are often not recorded by the utility at sufficient resolution that can allow the validation of the results presented in this research. However, the validation of results can be improved by conducting a face-to-face model demonstration and evaluation of the results with SMEs from the utility to evaluate different aspects of the model. This type of validation is part of the future work planned for this study.

5.4 Contributions of the Research

This dissertation makes various contributions to the body of knowledge and the body of practice in the area of the resilience of IWS systems. The main contribution of this research is the development and evaluation of a modeling approach that allows the analysis of the dynamics within components of IWS systems and the interactions among components in the context of short-term disruptions. This modeling approach tries to bridge several gaps in the research on IWS systems. In addition, the demonstration of the developed models in Chapter 2, Chapter 3 and Chapter 4 provides new insights and/or introduces new analysis approaches to support utilities' decision-making in the operation and the management of both the WDN and the non-piped water sources.

5.4.1 Contributions to the Body of Knowledge

This research contributes to the body of knowledge in the analysis of the resilience of the piped network in IWS systems. The resilience assessment framework (presented in Chapter 2) contributes to bridging the gap between the analysis of IWS systems under normal operation conditions and the analysis of CWS under disruptions. The developed framework contributes to the modeling of intermittent WDNs by incorporating household storage and supply scheduling in the simulation of network disruption and recovery. The framework also contributes to the analysis of intermittent WDNs by defining and evaluating network performance measures that are appropriate to IWS including the Serviceability Index and the Network-Average Tank Filling Ratio, which collectively can explain the network behavior at all stages of the disruption-recovery cycle. In addition, the framework adopted and evaluated four resilience metrics to assess the overall system resilience and the contribution of each resilience capacity (i.e., absorptive, adaptive, and restorative). The evaluation of the framework contributed to the body of knowledge by evaluating the impact of the supply inequity on the resilience of intermittent WDNs. In addition, the demonstration of the framework highlighted the trade-offs between network resilience, the number of affected households, and disruption duration. The evaluation of the framework also contributes to the body of knowledge by identifying the interactions of the main factors (namely household storage capacity, the timing of the occurrence of the disruption, the length of the disruption, and supply scheduling) that determine the system's resilience.

The analysis of the behavior of households in response to disruptions of the WDN (presented in Chapter 3) contributes to the body of knowledge in modeling the household decision making in IWS systems. Instead of modeling the household's behavior as simple choice from different non-piped sources, this research addressed other household behaviors related to their attitude towards the risk of running out of water (i.e., the timing of household's decision), the household's willingness to pay for faster delivery of non-piped water, and their preferences of waiting in-line for non-piped water. The analysis of the ABM in Chapter 4 shows that these household preferences have an impact on the performance of the market of non-piped water. In addition, the modeling of household behavior in this research adds to the body of knowledge by evaluating the impact of the household's knowledge about their water supply and storage and their prior experience with the system on their decisions.

The modeling and evaluation of the dynamics of the interactions between the stakeholders of the IWS system (Chapter 4) have several contributions to the body of knowledge. While prior studies in the analysis of the coupling of the components of the IWS focused on the long-term dynamics and interactions of stakeholders, the main contribution of the developed ABM is the analysis of the stakeholders' dynamics and interactions in the short-term in response to acute disruptions of the WDN. The evaluation of the ABM in the context of the case study city showed that short-term behavior and interactions of stakeholders have an impact on the performance of the IWS system under disruptions.

The proposed modeling approach for evaluating stakeholders' dynamics and interactions addresses the heterogeneity among households in terms of the impact of the disruption of the WDN and the heterogeneity in households' preferences related to timing, willingness to pay, and waiting times when obtaining non-piped water. In addition, the ABM incorporated the dynamics of the disrupted WDN and assessed their impact on the performance of the non-piped water market through the interactions of households, non-piped water vendors, and the utility's policy. The evaluation of the ABM contributed to the body of knowledge by evaluating the impact of the attributes of stakeholders on the trade-offs between the performance and the supply equality of the non-piped water market.

5.4.2 Contributions to the Body of Practice

This research contributes to the body of practice regarding both the operation and management of the intermittent WDN and the management of the non-piped water market. The resilience assessment framework described in Chapter 2 can assist the water utility in the operation of the IWS network under normal operation and under disruptions. Many IWS networks are operated, under normal operation conditions, based on personal experience of utility personnel and/or case by case demand-and-supply analysis. For the normal operation of the IWS network, the developed hydraulic simulation and the analysis of supply inequity can assist the utility in evaluating different operation strategies to improve the network performance. The framework can also be used by the utility to evaluate the impact of different disruption scenarios to be used in the decision-making for long-term resilience enhancement of the network. The utility can also use the framework to plan for short-term adaptive measures to improve network performance during disruptions. Another contribution to the body of practice is that the framework can assist in determining the critical assets in the network that have a higher priority for enhancement/rehabilitation due to the greater impact of their failure on the network performance.

Utilities can utilize the approach described in Chapter 3 by identifying the factors that affect the households' decisions during disruptions. The utility can use the results of the binary probit models to plan for policies aiming to change households' preferences (in the long-term) in order to improve the performance of the non-piped market during disruptions. For example, improving the process of obtaining water tankers at filling stations may affect the household manager's preferences about waiting in-line at the filling station.

The modeling of the dynamics and interactions of stakeholders in the IWS system makes several contributions to the body of practice. The developed ABM can be used by the city's water managers to assess the capacity of the non-piped water market, given different scenarios of intensities and durations of network disruptions in order to plan for intervention policy measures to improve the performance of the market. The results of the ABM indicate that possible improvements in the performance of the non-piped market can be achieved by implementing policies to encourage households to act early to disruptions, increase the number of available tankers, and/or increase the capacity of filling stations. Such policies include establishing effective communication with households during disruptions to provide information about the scale and the length of the disruption, providing free tankers to early orders to reduce the demand when households run out of water, and sharing water tankers between households.

The results of the ABM highlighted the importance of balancing the trade-off between the performance and the supply equality of the non-piped market. Greater demand for high-price tankers may increase the performance of the non-piped market, but it results in greater supply inequality among low- and high-income households. Similarly, increased demand for free tankers ensures greater supply equality, but it may affect the performance of the non-piped water market. The utility can use the ABM to test different policies to balance these trade-offs.

5.5 Recommendations for Future Work

Future research can focus on areas related to the limitations of this research. The components of this research, including the resilience assessment model, the modeling of households' decision making, and the ABM for the analysis of stakeholders' dynamics and interactions, were developed and evaluated in the context of one case study city in the Middle East. Future research can explore the applicability of this research in other IWS systems of similar system configurations in other cities. Future research may also modify and/or expand the developed models in this research to address IWS systems with different system configurations in terms of types of household storage and types of non-piped water sources.

One of the main areas for future research is related to the synthesis and the scaling analysis of the results of this research. Many of the results in this research, including the disruption patterns for IWS networks and the households' behavior during disruption, show repeated scalable patterns. Future research can further identify scalable functions and distributions that can approximate these patterns and analyze how they scale with the attributes of the disruption and the recovery of the network. Identifying scaling rules for the behavior of IWS systems under disruptions can help in expanding the results of this research to larger IWS networks with a greater number of households.

Future research can consider other variables that may affect the decision-making of households during disruptions. The results in Chapter 3 suggest that the water supply and consumption behavior of consumers living in apartments are different from the behavior of residents of houses. Variables specific to apartment consumers (related to the management of supply and demand in apartment buildings, the inclusion of bottled water as an alternative supply, consideration of temporary moving) are suggested for developing models specific to this class of households. Furthermore, the possibility of expanding the modeling of households' decision-making to other classes of water consumers (e.g., commercial water consumers) can be part of future research.

In analyzing the dynamics and interactions of stakeholders of the IWS system, it is recommended for future research to incorporate more dynamic utility behavior that changes during the time of the disruption. Additionally, future research can include the evaluation of the impact of additional utility policies suggested in this research (e.g., tanker sharing, providing free tankers for early orders, lifting price-controlling policies for tankers) that aim to manage and coordinate the non-piped water supply on the performance of the non-piped market.

Finally, this research adopted a household-level (bottom-up) approach in analyzing the resilience of IWS systems (by using hydraulic modeling and ABM) to account for the heterogeneity in network supply, disruption damage, and preferences among households. One of the disadvantages of these decentralized modeling approaches is the higher computational requirements. However, the results from this research suggest that the household heterogeneity can be abstracted using appropriate distributions. This abstraction of household heterogeneity allows future research to explore the use of macro-scale system analysis tools (such as network analysis tools and system dynamics) to analyze the resilience of IWS systems at the city-scale.

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APPENDIX A. RESULTS OF NETWORK PERFORMANCE FOR ALL DISRUPTION SCENARIOS

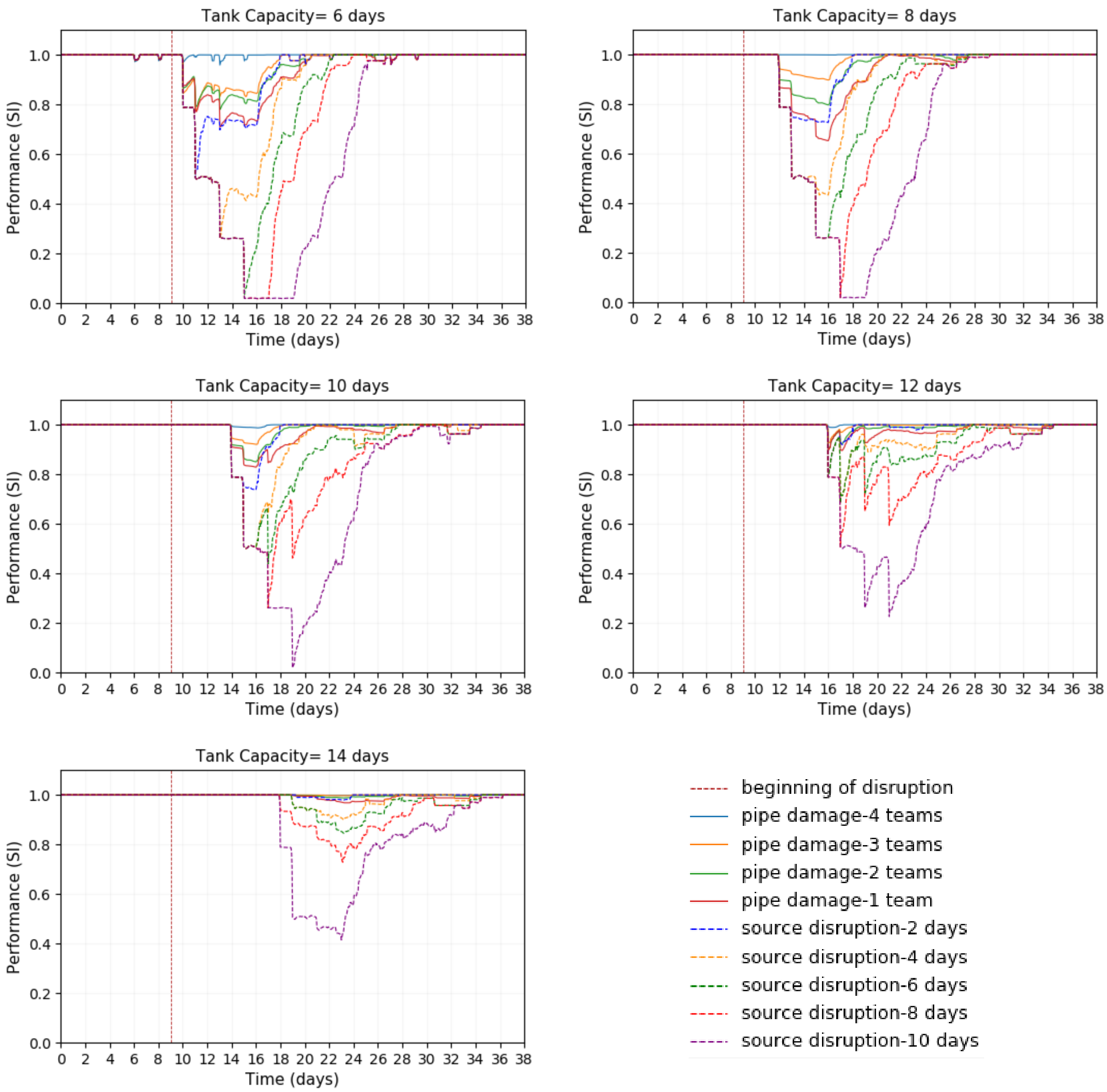

Figure A.1 Network's Serviceability Index (SI) for different disruption scenarios and household storage capacities (disruption occurs at the beginning of **Day 3** of the supply schedule)

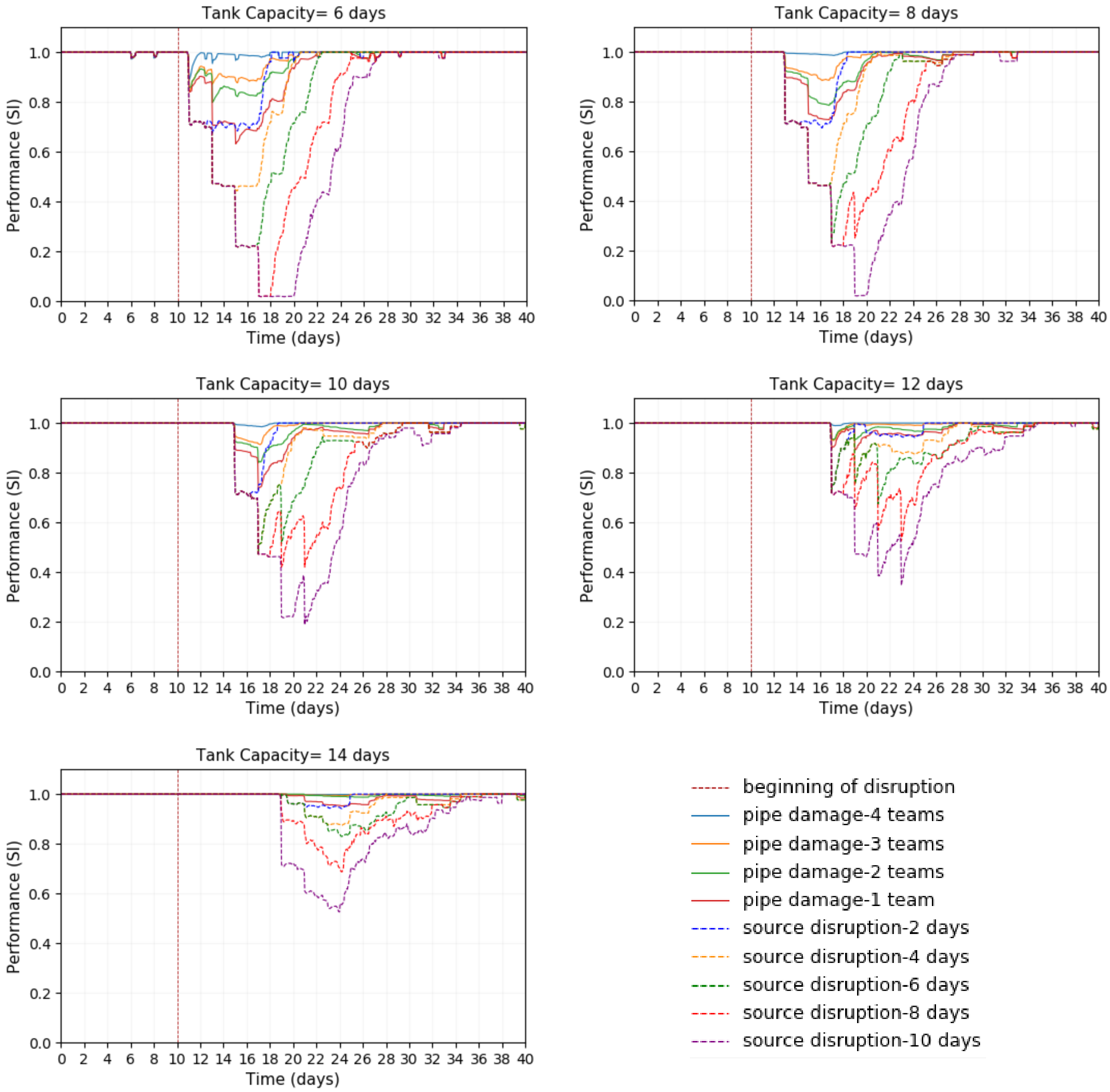

Figure A.2 Network's Serviceability Index (SI) for different disruption scenarios and household storage capacities (disruption occurs at the beginning of **Day 4** of the supply schedule)

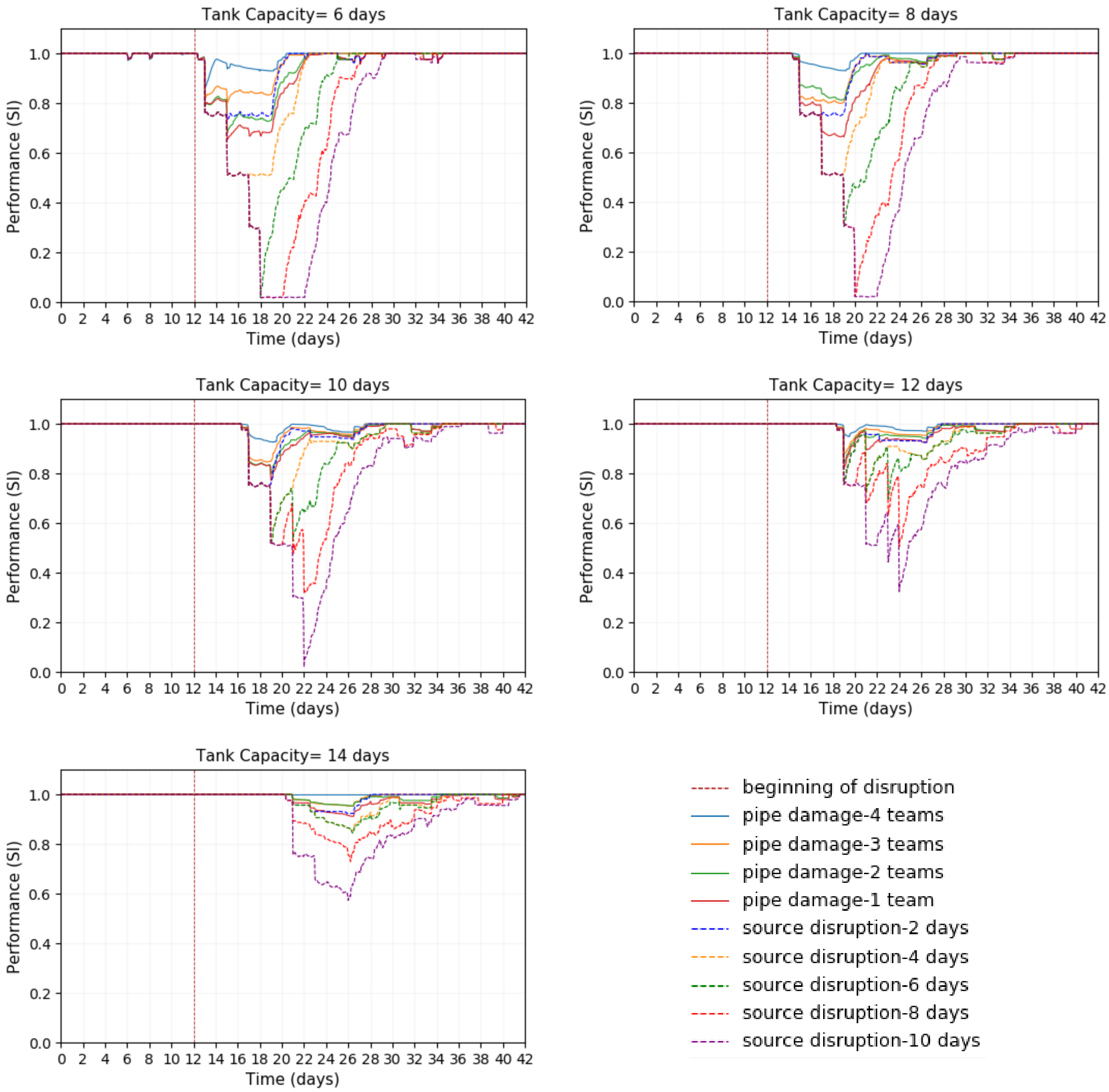

Figure A.3 Network's Serviceability Index (SI) for different disruption scenarios and household storage capacities (disruption occurs at the beginning of **Day 6** of the supply schedule)

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APPENDIX C. AMERICAN SOCIETY OF CIVIL ENGINEERS REPRINT PERMISSION (WORLD ENVIRONMENTAL AND WATER RESOURCES CONGRESS 2020)

PERMISSIONS <permissions@asce.org> Thu, Jun 18, 2020 at 4:59 PM
To: Saad Aljadhai <saljadha@purdue.edu>

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APPENDIX D. INSTITUTIONAL REVIEW BOARD EXEMPTION

PURDUE UNIVERSITY

HUMAN RESEARCH PROTECTION PROGRAM
INSTITUTIONAL REVIEW BOARDS

To:	ABRAHAM, DULCY M
From:	DICLEMENTI, JEANNIE D, Chair Social Science IRB
Date:	11/20/2018
Committee Action:(2)	Determined Exempt, Category **(2)**
IRB Action Date:	11 / 20 / 2018
IRB Protocol #:	1810021257
Study Title:	Water Consumption Behavior in Normal and Disrupted Scenarios in [redacted] City

The Institutional Review Board (IRB) has reviewed the above-referenced study application and has determined that it meets the criteria for exemption under 45 CFR 46.101(b).

Before making changes to the study procedures, please submit an Amendment to ensure that the regulatory status of the study has not changed. Changes in key research personnel should also be submitted to the IRB through an amendment.

General

- To recruit from Purdue University classrooms, the instructor and all others associated with conduct of the course (e.g., teaching assistants) must not be present during announcement of the research opportunity or any recruitment activity. This may be accomplished by announcing, in advance, that class will either start later than usual or end earlier than usual so this activity may occur. It should be emphasized that attendance at the announcement and recruitment are voluntary and the student's attendance and enrollment decision will not be shared with those administering the course.
- If students earn extra credit towards their course grade through participation in a research project conducted by someone other than the course instructor(s), such as in the example above, the students participation should only be shared with the course instructor(s) at the end of the semester. Additionally, instructors who allow extra credit to be earned through participation in research must also provide an opportunity for students to earn comparable extra credit through a non-research activity requiring an amount of time and effort comparable to the research option.
- When conducting human subjects research at a non-Purdue college/university, investigators are urged to contact that institution's IRB to determine requirements for conducting research at that institution.
- When human subjects research will be conducted in schools or places of business, investigators must obtain written permission from an appropriate authority within the organization. If the written permission was not submitted with the study application at the time of IRB review (e.g., the school would not issue the letter without proof of IRB approval, etc.), the investigator must submit the written permission to the IRB prior to engaging in the research activities (e.g., recruitment, study procedures, etc.). Submit this documentation as an FYI through Coeus. This is an institutional requirement.

Categories 2 and 3

- Surveys and questionnaires should indicate
  - only participants 18 years of age and over are eligible to participate in the research; and
  - that participation is voluntary; and
  - that any questions may be skipped; and
  - include the investigator's name and contact information.
- Investigators should explain to participants the amount of time required to participate. Additionally, they should explain to participants how confidentiality will be maintained or if it will not be maintained.
- When conducting focus group research, investigators cannot guarantee that all participants in the focus group will maintain the confidentiality of other group participants. The investigator should make participants aware of this potential for breach of confidentiality.

Category 6

- Surveys and data collection instruments should note that participation is voluntary.
- Surveys and data collection instruments should note that participants may skip any questions.
- When taste testing foods which are highly allergenic (e.g., peanuts, milk, etc.) investigators should disclose the possibility of a reaction to potential subjects.

You are required to retain a copy of this letter for your records. We appreciate your commitment towards ensuring the ethical conduct of human subjects research and wish you luck with your study.

Ernest C. Young Hall, 10th Floor - 155 S. Grant St. - West Lafayette, IN 47907-2114 - (765) 494-5942 - Fax: (765) 494-9911